



Nanotechnology
TOWARDS A MOLECULAR CONSTRUCTION KIT

EDITED BY ARTHUR TEN WOLDE

STT 60

STT Netherlands
Study Centre for
Technology Trends



Nanotechnology

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The Netherlands Study Centre for Technology Trends (STT), founded in 1968 by the Royal Institution of Engineers in the Netherlands, has the following aims:

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- to give wide publicity to its findings as a contribution to a more integrated picture of the future of society in the Netherlands and elsewhere.

STT addresses itself to industry, government, science, and the interested layman.

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Nanotechnology

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EDITED BY ARTHUR TEN WOLDE

1998

**NETHERLANDS STUDY CENTRE FOR TECHNOLOGY TRENDS (STT)
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Bottom up!

A previous publication of the Netherlands Study Center for Technology Trends (STT) 'Microsystem technology: exploring opportunities' (1994) argued that the miniaturization of electromechanical systems combined with several conventional physical and chemical technologies offers major opportunities for new products and processes. And indeed it does! Now, only a few years later, the size of experimentally manufactured microstructures is becoming so extremely small that a fundamental limit becomes relevant: the size of a single atom. Nanotechnology is concerned with manufacturing on the scale of molecules and atoms, a thousand times smaller than microsystems! This may lead to fundamentally new properties of materials. Over the next two decades, continued top-down mini-micro-nano-aturization will therefore result in even more (a thousand times more?) opportunities in information technology hardware: the chip of the 21st century is a nanochip. However, making things smaller and smaller is a path that becomes increasingly difficult to follow, full of potholes and roadblocks. The question then arises whether in the distant future, it might be feasible to construct a chip bottom-up from individual atoms and molecules using some kind of 'molecular construction kit'.

Believe it or not, such a construction kit is under development. Chemists are capable of synthesizing nanoparticles, 'large' and complex molecules, and assemblies from these molecules. These are the building blocks for future manufacturing. Physicists have developed needle devices that can move and sense individual atoms. Together with advanced synthesis, these are to be the tools of future manufacturing. Biologists are learning rapidly how nature accomplishes a variety of astonishing feats, such as growing a molecular motor that propels a bacterium through the water. The combination of such knowledge with the novel tools and building blocks fuels a new manufacturing technology that surpasses



both information technology and biotechnology. Nanotechnology is building nature's way. A completely new manufacturing approach could evolve. To this vision of future manufacturing I raise my glass and say: Bottom up!

Thanks to the enthusiasm of a large number of experts from the world of research and industry, both in the Netherlands, Flanders and abroad, STT has succeeded in surveying the most important fields of nanoscale science and technology today. It draws a picture of what the technology can offer us in the future and what needs to be done. The book is thus a good starting-point for building an acquaintance with these developments in the field of nanotechnology and gaining insight into the opportunities that it can offer. I hope it will generate ideas which will ultimately contribute to sustainable economic development.

A handwritten signature in blue ink, reading "H.N.J. Smits". The signature is stylized and written over a horizontal line.

Ir.dr. H.N.J. Smits
Member of the Executive Board of Rabobank Nederland
Chairman of STT
The Netherlands

Samenvatting

Arthur ten Wolde

VRAAGSTELLING

Nano betekent klein. De term staat voor ‘een miljardste’, en is geïnspireerd op het Oudgriekse woord voor dwerg, ‘nanos’. Nanotechnologie staat voor het bestuderen en manipuleren van piepkleine voorwerpen. De ‘nanowereld’ wordt bevolkt door atomen, moleculen, en moleculaire machines zoals het ribosoom, een cellulair orgaan dat eiwitten aanmaakt. Om een indruk te geven van de nanoschaal: in 1 nanometer (nm) – een miljardste van een meter – passen 6 koolstofatomen op een rij. In de STT-studie werden de volgende vragen gesteld: wat is nanotechnologie precies, en wat voor kansen biedt het?

WAT IS NANOTECHNOLOGIE?

Nanotechnologie is een opkomend veld van onderzoek en ontwikkeling gericht op toenemende controle over materiële structuren met afmetingen op nanoschaal (0,1 tot 100 nm) in tenminste een dimensie. Nanotechnologie is ook een cluster van opkomende technieken uit de vaste-stoftechnologie, biotechnologie, chemische technologie en raster-sondettechnologie, die 'top-down' en 'bottom-up' convergeren naar de nanoschaal. Top-down verwijst naar verkleining door het steeds fijner bewerken en afwerken van materialen, bottom-up naar synthese. De convergentie dicht de kloof tussen de vakgebieden.

Vandaag de dag bestaat nanotechnologie uit vier hoofdgebieden: nanoelektronica, nanomaterialen, moleculaire nanotechnologie, en microscopen met een oplossend vermogen op nanoschaal. Hoewel de grenzen vaag zijn, vertegenwoordigen deze velden verschillende technologieën die elk hun eigen kansen scheppen.

NANOELEKTRONICA

Nanoelektronica is hetzelfde als microelektronica, maar dan duizend keer kleiner. Ten behoeve van krachtiger computers is de dichtheid van transistoren op een chip gedurende de laatste decennia elke achttien maanden ruwweg verdubbeld. Deze tendens van exponentiële verkleining staat bekend als de wet van Moore. De halfgeleiderindustrie mikt op massaproductie van geïntegreerde schakelingen met details kleiner dan 100 nm in het jaar 2006.

Tot op heden worden microchips gemaakt met optische lithografie, een verkleiningstechniek. In essentie worden de patronen die een geïntegreerde schakeling definiëren aangebracht op een plak silicium door een lichtbundel via een masker te projecteren op het oppervlak. De technologie gebruikt verder lichtgevoelige deklagen, etsstappen en multilaagtechnieken. Optische lithografie is echter niet erg geschikt voor het produceren van chips met nano-details omdat de golflengte van het gebruikte licht te groot is. Voor de jongste generatie chips biedt ver-ultraviolet lithografie soelaas.

De huidige uitdaging is het vinden van een geschikte opvolger van ver-ultraviolet lithografie. Daarvoor staan verscheidene technieken kandidaat waarvan de werking is aangetoond. Extreem-ultravioletlithografie (EUVL) gebruikt straling met kortere golflengten dan ver-ultraviolet. Nog kortere golven worden gebruikt in nabije-röntgenlithografie (XRL). In plaats van licht kunnen ook deeltjes worden afgebeeld. Ionenbundel-afbeeldingslithografie gebruikt elektrische velden om ionen in het gewenste patroon te manoeuvreren, terwijl de projectielithografische SCALPEL-techniek magnetische velden gebruikt om elektronen af te buigen. De industrie is nog bezig deze opties te onderzoeken. De keuze zal afhangen van kritische factoren zoals snelheid en de kosten van maskerfabricage. Van een aantal andere verkleiningstechnieken voor het nanostructureren van oppervlakken moet het potentieel nog worden aangetoond. Atoomlithografie

gebruikt een patroon van staande-lichtgolven om een bundel van gekoelde atomen naar specifieke posities op een oppervlak te dirigeren. Raster-sondelithografie gebruikt atomair scherpe naalden voor het mechanisch verwijderen of aanbrengen van atomen in het gewenste patroon. Droog etsen, microcontactdrukken en ‘indrukstempelen’ (imprinting) zijn technieken voor patroonoverdracht. Elektronenbundel-lithografie is een belangrijk hulpmiddel voor maskerefabricage.

Nanostructuren kunnen ook ‘bottom-up’ gemaakt worden met chemische groeitechnieken. Deze laten atomen zichzelf organiseren in dunne lagen, draden, piramides, enzovoorts. Deze structuren kunnen quantumverschijnselen zoals tunneling en quantumopsluiting van elektronen teweegbrengen, hetgeen al heeft geleid tot commerciële producten waaronder quantumput-halfgeleiderlasers en elektronische geheugens gebaseerd op gigantische magnetoweerstand. Zodra een geschikte techniek voor massafabricage is ingevoerd en de huidige elektronische componenten zover mogelijk zijn verkleind, wordt het ontwikkelen van nieuwe componenten gebaseerd op quantumverschijnselen de volgende uitdaging voor de industrie.

Uiteindelijk – maar niet voor 2030 – zal aan de verkleining een einde komen als de atomaire schaal is bereikt. Overigens, Nederlandse wetenschappers hebben al aangetoond dat een enkel molecuul kan fungeren als transistor!

De nanoelektronica-industrie

Nanoelektronica zal krachtiger elektronische processoren en geheugens opleveren, te integreren in computers, telefoons, auto’s, enzovoorts. Dit betekent een wereldmarkt van honderden miljarden gulden, waardoor nanoelektronica de drijvende kracht vormt achter de huidige ontwikkeling van nanotechnologie. Raster-sondemicroscopen bieden op korte termijn kansen voor hoge-dichtheid gegevensopslag. Echter, zelfs de deskundigen weten niet of verkleining zal blijven doorgaan volgens de wet van Moore. Verscheidene factoren, zoals toegenomen kosten van verkleining tegenover afnemende meerwaarde, dreigen de huidige afdaling in de nanowereld te vertragen.

NANOMATERIALEN

Nanomaterialen zijn materialen die een welbepaalde morfologie met nanofmetingen bevatten. Het eenvoudigste voorbeeld is een poeder van deeltjes met doorsneden tussen 1 en 100 nm (nanodeeltjes). Nanodeeltjes kunnen worden gemaakt met gasfasesynthese. De gewenste atomen worden verdampt van een oppervlak en vormen een dicht gas. Afkoeling van het gas leidt tot de groei van nanodeeltjes, zoals bij regendruppels in een wolk.

De deeltjesgrootte kan worden geregeld via de procesparameters. Samenklontering kan worden vermeden door snelle afkoeling. Filteren op deeltjesgrootte wordt ook toegepast. Het resultaat kan bijvoorbeeld worden bekeken door een

elektronenmicroscop met een oplossend vermogen op nanoschaal. Nanodeeltjes kunnen ook in oplossing worden gesynthetiseerd met conventionele technieken uit de colloidchemie (de scheikunde van deeltjes met afmetingen tussen 1 en 1000 nm). In dit geval groeien nanodeeltjes uit kleine moleculen die samenvlokken in een oververzadigde oplossing. Op de deeltjes kunnen functionele moleculen worden aangebracht. Ook de vorm en samenstelling van de deeltjes kunnen worden gevarieerd, maar hun grootte laat zich wat minder goed regelen dan bij gasfasesynthese.

De gesynthetiseerde nanodeeltjes worden verzameld door de damp of suspensie te laten neerslaan. Op deze manier kan een nanopoeier worden gevormd dat geschikt is voor verdere verwerking. Wel is het poeder zeer reactief door het grote oppervlak per volume-eenheid. Tijdens het verwerkingsproces is voorzichtigheid daarom geboden, enerzijds om oxidatie van het poeder tegen te gaan en anderzijds om gezondheidsrisico's te voorkomen. Ook nanogestructureerde deklagen, harige structuren of bulkmaterialen kunnen worden verkregen. Comprimeren is mogelijk door ze bijvoorbeeld heet samen te persen. De overgang van 'micro'- naar 'nano'materialen biedt verscheidene voordelen. Ten eerste levert het een enorme oppervlaktevergroting op.

Materiaaleigenschappen worden overheerst door oppervlakte-eigenschappen. Het materiaal kan bijvoorbeeld lichtgevoelig worden gemaakt door elk deeltje te bedekken met een kleurstof. Ten tweede veroorzaakt de afname van de deeltjesgrootte zowel mechanische voordelen als quantumeffecten. De belemmerde voortplanting van roosterverstoringen leidt bijvoorbeeld tot sterke en harde metalen, en de bevordering van kruip van atomen via diffusie leidt tot buigzaam 'superplastisch' keramiek tijdens bewerking onder verhitting.

Quantumopsluiting maakt het mogelijk materiaal'constanten' te veranderen, zoals blijkt uit de blauwverschuiving van het optische spectrum van nanodeeltjes.

De nanomateriaalindustrie

Nanomaterialen zullen op vrijwel alle gebieden worden toegepast. Sommige producten zijn nu al op de markt, zoals zonnebrandolie met ultraviolet-absorberende nanodeeltjes en brillen met een krasvaste nanodeklaag. Andere hebben bewezen mogelijkheden en worden gedurende de komende 5 tot 15 jaar op de markt verwacht, zoals organische zonnecellen, antiroest-deklagen, taaiere en hardere snijwerktuigen, fotokatalytische luchtfilters, duurzamere medische implantaten, en snel brandende metaalpoeders voor het leger. De huidige wereldmarkt wordt geschat op 20 miljard gulden en groeit. Binnen 10 tot 20 jaar kunnen nanogestructureerde materialen ook essentiële ingrediënten vormen voor toekomstige nanoelektronische componenten gebaseerd op quantumeffecten zoals 'superparamagnetisme'. Intussen wordt verwacht dat de nanomateriaaltechnologie zich verder ontwikkelt in de richting van moleculaire nanotechnologie.

MOLECULAIRE NANOTECHNOLOGIE

Moleculaire nanotechnologie betreft de synthese ('bottom-up') van nanostructuren met precieze beheersing van de driedimensionale positie van individuele atomen en moleculen (een 'moleculaire bouwdoos'). Hun positie bepaalt ook de eigenschappen van de toepassingen, zoals in moleculaire elektronische componenten of moleculaire machines.

De synthese kan chemisch, biologisch of mechanisch van aard zijn. Chemische synthese omvat verschillende vormen van assemblage. Covalente assemblage houdt in dat stereo-elektronische informatie is voorgeprogrammeerd in de moleculaire eenheden, en staat de opbouw toe van rigide, complexe systemen zoals moleculair lint. Zelfassemblage is "de spontane groepering van moleculen onder evenwichtsomstandigheden tot stabiele, structureel goed gedefinieerde aggregaten op basis van niet-covalente bindingen". Voorbeelden zijn moleculaire kooien die een zwak gebonden moleculaire dipool bevatten, in elkaar gehaakte ringen, en zelfassemblerende monolagen.

Biologische concepten en mechanismen worden op verschillende manieren overgenomen in de materiaaltechnologie. Levende organismen kunnen mineralen, polymeren en metaaldeeltjes van nano-afmetingen synthetiseren.

Biomimetische synthese lijkt op de manier waarop zeeschelpen groeien door biomineralisatie. De bacteriële zweepstaartmotor, het ribosoom, DNA-moleculen, fotoactieve eiwitten, en het fotosyntheseproces zijn voorbeelden uit de levende natuur die worden bestudeerd met het oog op de fabricage van kunstmatige moleculaire machines en elektronische componenten op de lange termijn. Ten slotte kunnen driedimensionale nanostructuren ook mechanisch worden gemaakt met raster-sondemicroscopen via een nog grotendeels theoretisch proces onder de naam mechanosynthese.

Vele aspecten van moleculaire nanotechnologie kunnen worden gesimuleerd op een computer. Simulaties hebben bijvoorbeeld de geleidende eigenschappen van koolstof nanobuisjes verklaard. Het huidige onderzoek omvat behalve het vouwgedrag van eiwitten ook de haalbaarheid en eigenschappen van moleculaire schakelaars, motoren en lagers als aparte componenten van toekomstige moleculaire machines.

Toekomstige toepassingen

Nanoblaasjes zoals liposomen (bolvormige dubbellagige membranen), dendriermen (vertakte polymeren) en mogelijk ook gemodificeerde fullerenen zijn uitstekende kandidaten voor het efficiënt afleveren van medicijnen op die plaats in het menselijk lichaam waar activiteit gewenst is. Er ontstaan ook nieuwe kansen voor katalytische materialen en sensoren. Biochip-arrays – die al commercieel worden geproduceerd – zijn een krachtig diagnostisch product van microsteemtechnologie en biotechnologie; door verdere verkleining kan worden verwacht dat ze binnen twintig jaar het nanoregime bereiken. Moleculaire sen-

soren zijn ultragevoelig omdat een enkel molecuul een meetbaar signaal oplevert. Plastic elektronica en platte beeldschermen bieden mogelijkheden voor elektronische toepassingen op de korte termijn, en hoge-dichtheid geheugens, ultrasnelle processoren en moleculaire elektronica op de lange termijn. Dit laatste vereist niet alleen een doorbraak in het snel en betrouwbaar aanspreken van individuele moleculen; er doemen ook vele andere problemen op. Aangenomen dat deze worden opgelost, dan zal moleculaire nanotechnologie beslist leiden tot nieuwe elektronische componenten. Moleculaire motoren ten slotte komen voor in de natuur en worden intensief bestudeerd. Op de lange termijn behoort het ontwerpen en synthetiseren van gemodificeerde of zelfs kunstmatige moleculaire motoren tot de mogelijkheden. Het zelfde kan worden gezegd van Drexler's 'moleculaire monteur', een moleculaire machine die andere moleculen produceert.

MICROSCOPEN MET EEN OPLOSSEND VERMOGEN OP NANOSCHAAL

Microscopen met een oplossend vermogen voor details van 100 nm of kleiner vormen een nieuwe klasse van apparatuur voor het afbeelden van het ultraklein. Dit boek behandelt raster-sondemicroscopie en optische microscopie met een oplossend vermogen op nanoschaal. Overigens dient te worden vermeld dat andere technieken zoals NMR (magnetische kernspinresonantie)-spectroscopie en röntgenkristallografie zich eveneens ontwikkelen tot krachtige en belangrijke technieken, vooral voor het afbeelden van driedimensionale nanostructuren.

De raster-tunnelmicroscop (STM) is ontwikkeld in het begin van de jaren tachtig en heeft een sterke impuls gegeven aan de nanowetenschap. Het apparaat gebruikt een atomair scherpe naald om hoogteverschillen aan het oppervlak van een monster af te tasten, een beetje zoals een ouderwetse platenspeler. De naald hangt ongeveer twee atomaire diameters boven het oppervlak en geleidt een tunnelstroom van elektronen. Een minuscule verandering in de afstand tussen naald en oppervlak leidt tot een enorme verandering in de stroom. De truc is de stroom constant te houden door de naald naar boven en beneden te bewegen terwijl hij langs het oppervlak schuift. Deze corrigerende bewegingen volgen de heuvels en dalen van het oppervlak en worden door een computer omgezet in een beeld met atomair oplossend vermogen. Raster-tunnelmicroscopen kunnen tegenwoordig worden bedreven in vacuüm, lucht, in een gasatmosfeer of in een vloeistof, en onder hoge temperatuur en druk. Ze kunnen oppervlakteprocessen direct filmen. Behalve voor het afbeelden, kunnen ze ook worden gebruikt voor fabricage of herstel van nanostructuren. Hun belangrijkste beperking is dat ze alleen werken voor elektrisch geleidende monsters zoals metalen en halfgeleiders.

De atomaire-krachtmicroscop (AFM) voelt kracht in plaats van stroom. Hierdoor is de analyse van isolerende oppervlakken zoals polymeren mogelijk

met een typisch oplossend vermogen van 10 nm. De naald kan in contact met het oppervlak, los ervan, of tikkend over het oppervlak worden geschoven. Chemisch specifieke metingen zijn mogelijk door de naald te voorzien van een deklaag. Vele krachten worden gebruikt, waaronder magnetisme.

De nabije-veld optische rastermicroscopie (SNOM) detecteert licht. Een speciale naald, bijvoorbeeld een optische fiber met een 60 nm opening, heeft interactie met het licht bij het oppervlak direct eronder. De diffractielimiet voor licht wordt hierdoor omzeild. De naald kan fungeren als lichtbron of als collector en wordt gebruikt in verschillende configuraties. Meting van de wrijvingskracht helpt om naaldbreuk te voorkomen. De methode maakt de afbeelding mogelijk van monolagen, chromosomen, cellen, en de beweging van individuele fluorescerende moleculen op een oppervlak. Optische microscopie kan overigens ook zonder naald een oplossend vermogen op nanoschaal bereiken. De positie van kleine deeltjes kan worden gevolgd met een nauwkeurigheid van 1 nm. Optische pin-cetten worden gebruikt om deeltjes te manipuleren en om de elastische eigenschappen van DNA-moleculen te bepalen.

De raster-sondemicroscopie-industrie

Het nut van raster-sondemicroscopen als hulpmiddel voor analyse heeft geleid tot de snelle ontwikkeling van een hightech industrie met een jaarlijkse omzet van 400 miljoen gulden. Ze worden bijvoorbeeld toegepast voor productcontrole in de microelektronica en in de optische industrie, in de materiaalwetenschappen en biologie, en voor elektrochemische metingen. Er ontstaan kansen voor gegevensopslag, nanofabricage van prototypen, industriële procescontrole, biosensoren en onderwijs.

CONCLUSIE EN TOEKOMSTBEELD

De nanotechnologie bevindt zich nog in haar prille jeugd. Onderling afgestemde onderzoeksinspanningen zijn nodig om haar inderdaad te ontwikkelen tot een sleuteltechnologie voor de 21ste eeuw, waarbij vaste-stoftechnologie en biotechnologie zullen worden overtroffen. De toenemende beheersing over de rangschikking van atomen zal nieuwe mogelijkheden scheppen op *alle* gebieden, van duurzame tot militaire producten. Veel materialen, elektronica, en medische toepassingen zullen binnen 20 jaar op de markt verschijnen. Op middellange termijn kunnen ook meer sensationele producten zoals zelfreinigend textiel worden verwacht. Op de lange termijn kan nanotechnologie onze ideeën over 'leven' op de helling zetten en daardoor ethische bezwaren oproepen die lijken op die tegen biotechnologie. Ook de moleculaire productie van macroscopische producten met Drexler's nanomachines zou kunnen worden gerealiseerd. Futurologen voorzien daardoor zelfs een omwenteling van onze economische structuur en het begin van het zogenaamde 'diamanten tijdperk', omdat de productiekosten van bijvoorbeeld diamant drastisch zouden dalen. Deze laatste visie wordt echter niet gedeeld door STT.

Executive summary

Arthur ten Wolde

FOCUS OF THE STUDY

Nano means small. The term stands for ‘one billionth’, and has been inspired by the ancient Greek word ‘nanos’, meaning dwarf. Nanotechnology is the study and manipulation of tiny objects. The ‘nanoworld’ is populated by atoms, molecules, and molecular machines such as the ribosome, a cellular organ producing proteins. To give an impression of the nanoscale: 1 nanometer (nm) – one billionth of a meter – can contain 6 carbon atoms in a row. In the STT-study, the following questions were posed: what exactly is nanotechnology, and what opportunities does it offer?

WHAT IS NANOTECHNOLOGY?

Nanotechnology is an emerging field of research and development dedicated to increasing the control over material structures of nanoscale size (0.1 to 100 nm) in at least one dimension. Nanotechnology is also a cluster of emerging techniques from solid-state technology, biotechnology, chemical technology and scanning-probe technology that converge 'top-down' and 'bottom-up' to the nanoscale. Top-down refers to the increasingly precise machining and finishing of materials from the macroscopic down to nanoscopic scales, bottom-up to synthesis from individual molecules or atoms. The convergence is closing the gap between the disciplines.

Today, nanotechnology consists of four major fields: nanoelectronics, nanomaterials, molecular nanotechnology, and nanoscale-resolution microscopes. Although the boundaries are fuzzy, these fields represent different enabling technologies creating their own opportunities.

NANOELECTRONICS

Nanoelectronics is the same as microelectronics, but a thousand times smaller. In order to produce more powerful computers, the density of transistors on a chip has roughly doubled every eighteen months over the last decades. This trend of exponential miniaturization is known as Moore's Law. Mass production of integrated circuits with features below 100 nm is planned before the year 2006.

Up to now, microchips have been manufactured using a top-down technique called optical lithography. Basically, the patterns defining an integrated circuit are transferred to a wafer by projecting a light beam through a mask. The technology further involves photoresists, etching steps and layering techniques. However, optical lithography is not very suited to produce chips with nanosize features because the wavelength of the light is too long. For the current generation of chips, deep-ultraviolet lithography gives room for improvement.

The current challenge is to find a viable successor for deep-ultraviolet lithography. Various demonstrated techniques are being investigated for further development. Extreme-ultraviolet lithography uses radiation with shorter wavelengths than deep ultraviolet. Even shorter waves are used in x-ray proximity lithography. Instead of light, particles can be projected. Ion-beam projection lithography uses electric fields to steer ions into the desired pattern, whereas SCALPEL (scattering with angular limitation projection electron-beam lithography) uses magnetic fields to maneuver electrons. The industry is still investigating these options. The choice will depend on critical factors such as speed and the costs of mask fabrication.

Several other top-down approaches to achieve nanostructuring of surfaces are still in the lab phase, but may be applicable in the future. Atom lithography uses a pattern of standing light waves to steer a beam of cooled atoms to specific

locations on a surface. Scanning-probe lithography uses atomically sharp needles for the mechanical removal or deposition of atoms in the desired pattern. Dry etching, microcontact printing and imprinting are techniques for pattern transfer. Electron-beam lithography using serial writing is a very useful tool for mask fabrication.

Nanoscale structures can also be fabricated with bottom-up chemical growth techniques. These direct atoms to organize themselves into films, wires, pyramids etc. These structures can induce quantum phenomena such as tunneling and quantum confinement ('trapping') of electrons, which have already led to commercial products such as quantum-well semiconductor lasers and random-access memories based on giant magnetoresistance (GMR). Once a suitable technique for mass fabrication has been implemented and the present-day electronic components have been scaled down as far as possible, the next challenge for the industry will be to develop novel components based on quantum phenomena.

Eventually – but not before 2030 – miniaturization is bound to come to an end when the atomic scale is reached. Incidentally, Dutch scientists have already demonstrated that a single molecule can function as a transistor!

The nanoelectronics industry

Nanoelectronics will create more powerful electronic processors and memories, to be integrated in computers, telephones, cars and so on. This amounts to a world market of hundreds of billions of dollars, which makes nanoelectronics the driving force behind the current development of nanotechnology. Scanning probes are providing opportunities for high-density data storage in the near future. However, even the experts don't know if miniaturization will progress according to Moore's law. Various factors, such as increased costs of miniaturization and decreasing added value, may well slow down the current descent into the nanoworld.

NANOMATERIALS

Nanomaterials are materials containing a controlled morphology of nanoscale dimensions. The simplest example is a powder consisting of particles with diameters between 1 and 100 nm (nanoparticles). Nanoparticles can be obtained by gas-phase synthesis. The desired atoms are evaporated from a surface, forming a dense gas. Cooling of the gas induces the growth of nanoparticles, like rain drops in a cloud. The particle size can be fairly well controlled by the process parameters. Agglomeration can be avoided by rapid cooling. Size-selective filtering is also applied. The particles can be characterized using, for instance, a nanoscale-resolution electron microscope.

Nanoparticles can also be synthesized in solution, using conventional techniques from colloid chemistry (the chemistry of particles with dimensions

between 1 and 1000 nm). In this case, nanoparticles grow out of small molecules flocking together in a supersaturated solution. The particles can be coated with functional groups. Their shape and composition can also be controlled, but size control is more difficult than with gas-phase synthesis.

The synthesized nanoparticles are collected by letting the vapor or suspension precipitate. In this way a nanopowder can be formed, to be processed further for applications. Due to the large surface area per volume, the powder is highly reactive. Caution is therefore needed to prevent oxidation of the powder and also to prevent health hazards during handling. Nanostructured coatings, whiskers or bulk materials can also be obtained. They can be compacted using, for instance, hot pressing.

The transition from 'micro' to 'nano' particles offers several advantages. First, it implies an enormous increase in surface area. Bulk properties become governed by surface properties. For instance, the material can be made light-absorbing by coating the particles with a dye. Second, the particle size reduction induces both mechanical advantages and quantum effects. For instance, the hindered propagation of lattice perturbations leads to strong and hard metals, and enhanced diffusional creep leads to ductile 'superplastic' ceramics during processing at elevated temperatures. Quantum confinement allows for control over material 'constants', as demonstrated in the blue shift of the optical spectrum of nanoparticles.

The nanomaterials industry

Nanomaterials will find applications in many areas. Some products are already on the market, such as sunburn lotions containing ultraviolet-absorbing nanoparticles and spectacles with a scratch-resistant nanocoating. Others have a demonstrated potential and are expected to appear on the market within the next 5 to 15 years, such as organic solar cells, anti-corrosion coatings, tougher and harder cutting tools, photocatalytic air purifiers, longer-lasting medical implants, and fast-burning metal powders for the military. The world market volume is estimated at ten billion dollars and growing. Within 10 to 20 years, nanostructured materials could also form vital ingredients for future nanoelectronic components based on quantum effects such as superparamagnetism. Meanwhile, nanomaterials technology is expected to develop further in the direction of molecular nanotechnology.

MOLECULAR NANOTECHNOLOGY

Molecular nanotechnology concerns the bottom-up synthesis of nanostructures with precise three-dimensional positional control of individual atoms and molecules (a ‘molecular construction kit’). Their position also determines the properties of the applications, as in molecular electronic devices or molecular machines. The synthesis can be of a chemical, biological or mechanical nature. Chemical synthesis involves some form of assembly. Covalent assembly implies that stereoelectronic information is pre-programmed in the molecular units, and allows for the construction of rigid, complex systems such as molecular tape. Self-assembly is “the spontaneous association of molecules under equilibrium conditions into stable, structurally well-defined aggregates joined by non-covalent bonds”. Examples are molecular cages containing a weakly bound dipole molecule, interlocked rings, and self-assembling monolayers.

Biological concepts and mechanisms are being adapted into materials technology in various ways. Bio-organisms can synthesize nanosized minerals, polymers and metal particles. Biomimetic synthesis resembles the way sea shells grow by biomineralization. The bacterial flagellar motor, the ribosome, DNA molecules, photoactive proteins and the photosynthesis process are examples from nature that are being studied with the manufacturing of artificial molecular machines and devices as a long-term aim. Finally, three-dimensional nanostructures can also be fabricated mechanically using scanning probes, a still largely theoretical process dubbed mechanosynthesis.

Many aspects of molecular nanotechnology can be simulated on a computer. Simulations have, for instance, explained the conductive behavior of carbon nanotubes. In addition to the folding behavior of proteins, current research includes the feasibility and properties of molecular switches, motors, and bearings as separate components of future molecular machines.

Future applications

Nanosized vesicles such as liposomes (spherical bilayer membranes), dendrimers (branched polymers) and possibly also modified fullerenes are excellent candidates for the efficient delivery of drugs to their desired site of action in the human body. Molecular nanotechnology could also produce useful catalytic materials. Biochip arrays, already produced commercially, are a powerful diagnostic product of microsystem technology and biotechnology; ongoing miniaturization can be expected to push them into the nanoregime within twenty years. Molecular sensors are ultra-sensitive because a single molecule produces a measurable signal. Opportunities for electronic applications include plastic electronics and flat panel displays in the near-term, and high-density memories, ultrafast processors and molecular electronics in the longer term. Fast and reliable addressing of individual molecules is required, and many additional problems loom ahead. Provided that these are tackled, molecular nanotechnology

will undoubtedly lead to new electronic devices. Finally, molecular motors exist in nature and are under intensive study. In the long term it may very well be possible to design and synthesize modified or even artificial molecular motors. The same can be said about Drexler's molecular assembler, a molecular machine producing other molecules.

NANOSCALE-RESOLUTION MICROSCOPES

Nanoscale-resolution microscopes form a new class of tools for imaging of the ultrasmall with a resolution below 100 nm. This book discusses scanning probe microscopy and nanoscale-resolution optical microscopy. It should be noted that other techniques such as NMR (nuclear magnetic resonance) spectroscopy and x-ray crystallography are becoming very powerful and important as well, especially for imaging three-dimensional nanostructures.

The scanning tunneling microscope was developed in the early eighties and gave a strong boost to nanoscale science. It uses an atomically sharp needle to sense height variations at the surface of a specimen, a bit like an old-fashioned record player. The tip hangs above the surface at a distance of about two atomic diameters and emits (or receives) a current of tunneling electrons. A minute change in the tip-surface distance induces a major change in the current. The trick is to keep the current constant by moving the tip up and down while it scans the surface. These correcting movements follow the hills and valleys of the surface, and are converted into a computer image with atomic resolution. Scanning tunneling microscopes can now be operated in vacuum, air, gases or liquids, at low and elevated temperatures and pressures. They can produce real-time videos. In addition to imaging, they can also be used for nanofabrication or repair. Their main limitation is that they need electrically conductive samples such as metals and semiconductors.

The atomic force microscope senses force instead of current, which allows the analysis of insulating surfaces such as polymers with a typical resolution of 10 nm. The tip can be scanned either in contact with the surface, without contact or both in tapping mode. Chemically specific measurements can be made by coating the tip. Many types of forces are employed, including magnetism.

The scanning near-field optical microscope senses light. A special tip, such as an optical fiber with a 60-nm aperture, interacts with the light at the surface directly below it. The diffraction limit for light is thereby circumvented. The tip can function as a light source or collector and is used in various configurations. Shear-force measurement helps to prevent tip fracture. The method allows the imaging of monolayers, chromosomes, cells and the movement of single fluorescent molecules on surfaces. Finally, nanoscale-resolution optical microscopy can be achieved even without using a tip. The position of small particles can be tracked with a precision of 1 nm. Optical tweezers have been used to manipulate particles and to determine the elastic properties of DNA molecules.

The scanning probe industry

The usefulness of scanning probes as a tool for analysis has led to the rapid development of a 200 million dollar high-tech industry. They are, for instance, applied for product inspection in the microelectronics and optics industry, for materials science and biology, and for electrochemical measurements.

Opportunities lie in data storage, nanofabrication of prototypes, industrial process control, biosensors and education.

CONCLUSION AND OUTLOOK

Nanotechnology is still in its infancy. Concerted research efforts are needed to realize its potential as a key technology for the 21st century, surpassing solid-state technology and biotechnology. The increasing control over the arrangement of atoms will create new possibilities for manufacturing in all areas, including sustainable as well as military products. Many materials, electronics and medical applications will enter the market within 20 years. Fancier products such as self-cleaning textiles can be expected to appear in the mid term. In the long term, nanotechnology might modify the concept of life, invoking ethical objections resembling those against biotechnology. Molecular manufacturing of macroscopic products using Drexler's nanomachines could be realized. Futurologists therefore foresee a revolution of our economic structure and the beginning of the so-called 'diamond age', caused by a drastic reduction the manufacturing costs of, for example, diamond. However, this latter vision is not shared by STT.

1

Introduction

1.1 WHAT IS NANOTECHNOLOGY?

A. ten Wolde

Small, smaller, Smalley

Nano means small. It is a standard prefix in the list of physical units: milli, micro, nano, meaning $1/1000$, $1/1000,000$, and $1/1000,000,000$. It has been inspired by the ancient Greek word ‘nanos’, meaning dwarf.

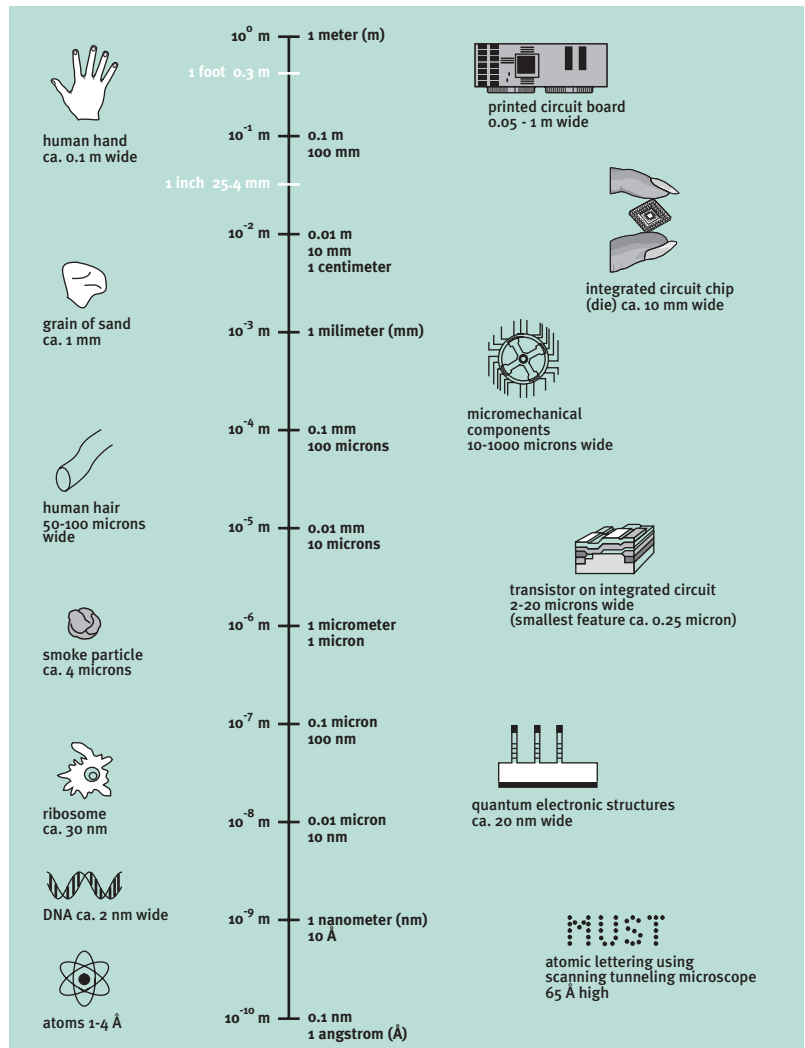
The term nanotechnology means *nanometer*-scale science and technology, where 1 nanometer (nm) is one millionth of a millimeter. Figure 1.1.1 gives a feeling for the ‘nanoworld’, which is populated by atoms, molecules, and molecular machines such as the ribosome, a cellular organ producing proteins in our body.

This book uses the following working definition:

Nanotechnology is an emerging field of research and development dedicated to increasing the control over material structures of nanoscale size (0.1 to 100 nm) in at least one dimension.

Figure 1.1.1

From the 'real' to the nanoworld.
Figure adapted from the Office of
Technology Assessment.



Strictly speaking nanotechnology is not yet a technology, because complete portfolios of available techniques to transform an idea into a commercial product hardly exist. It is a cluster of emerging techniques that converge 'top-down' and 'bottom-up' from physics, chemistry and biology to the same nanoscale (figure 1.1.2). The term 'nanotechnology' was introduced by Taniguchi in 1974 to refer to the increasingly precise (top-down) machining and finishing of materials. However, the term was popularized by K. Eric Drexler¹ during the 80's, when he introduced the concept of molecular manufacturing. For Drexler and his followers, the term means *molecular* nanotechnology (the bottom-up approach), and implies the precise three-dimensional positional control of individual atoms and molecules (chapter 4). Biologists have started to use terms such as bioscience and nanobiotechnology only in the 90's.

1 <http://www.foresight.org/FI/Drexler.html>

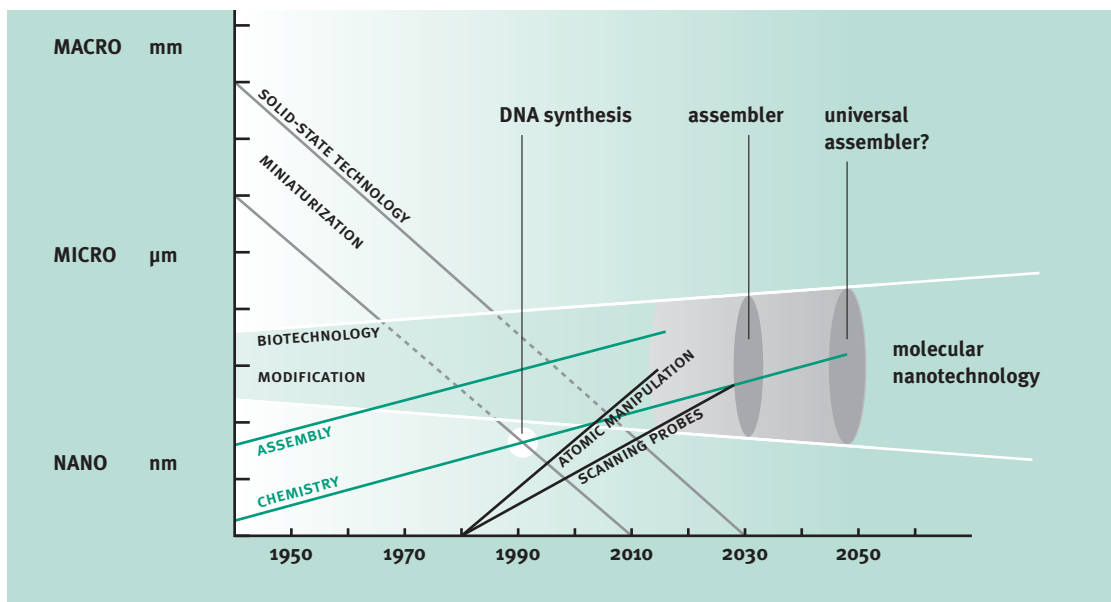


Figure 1.1.2
Converging disciplines: emerging techniques from solid-state technology, biotechnology, chemistry and scanning-probe technology are converging on the nanoscale. Figure inspired by [Rohrer, 1996]

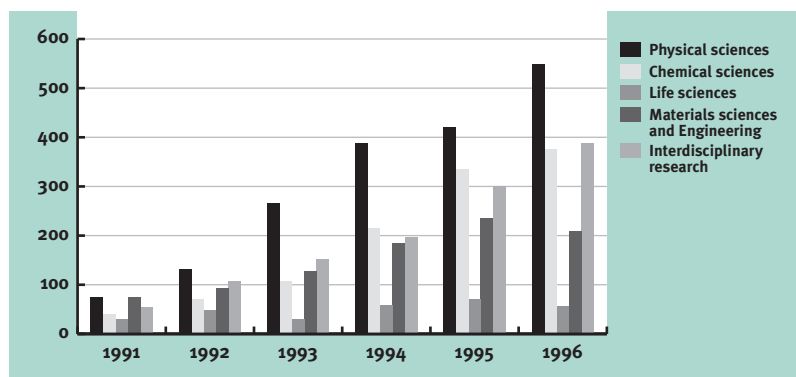
The convergence closes the gap between classical chemistry, biotechnology and solid-state technology. Classical chemistry synthesizes molecules that are usually smaller than several nm, while solid-state technology fabricates structures without molecular positioning that are usually larger than 100 nm. These classical structures are not considered in this study. Structures that are larger than 100 nm in three dimensions are only taken into account if synthesized with atomic or molecular positioning and non-crystalline (macro- or supramolecular structures). The convergence of disciplines on the nanoscale has already led to fruitful interdisciplinary cooperation. For instance, biotechnology has been modifying macromolecules for decades while chemists developed the chemical synthesis of increasingly complex macromolecules. DNA synthesis is now a useful tool for biotechnology. Likewise, nanotechnology enables the trend of miniaturization to continue until the atomic scale has been reached, possibly with the help of chemical self-assembly of nanostructures such as quantum dots. Scanning probes, developed since the early eighties, allow for the manipulation of individual atoms. The combination of all these techniques is leading to the new field of molecular nanotechnology, which is expected to allow the development of artificial molecular machines such as a molecular motor. An artificial molecular machine of particular importance is the so-called assembler. Like the ribosome, this will be a molecular machine producing other molecules. If, in addition to this, it proves possible to devise and develop a ‘genetic’ programming scheme that tells the assembler what molecules to produce and how to assemble them into a specific supramolecular nanostructure, we might speak of a ‘universal’ assembler that can produce ‘a healthy bite’ of all possible material structures [Merkle, 1997]. In the view of Nobel prize winner Richard Smalley², a

² <http://cnst.rice.edu/reshome.html>

universal assembler might look like a nanoscale robot equipped with arms and enzymes as ‘sticky fingers’ [Smalley, 1997]. However, this is still a theoretical construct. And even if it proves possible to develop it, the question remains: is it possible to devise a fabrication scheme that can produce macroscopic quantities of the desired material structure? The standard answer to this is that an assembler might be programmed to make a copy of itself every now and then during the fabrication process. This certainly is a way to ensure an exponential growth of the fabrication speed, just as a living organism grows out of a single cell by cell division. However, without intricate programming of this process, it is hard to see how the assemblers and the desired structures can be prevented from forming a kind of mixed ‘blob’ consisting of micro-fragments of the desired product, with many assemblers trapped and cut off from the necessary feed-stock of atoms and molecules. Living organisms have solved this problem, but need several months to grow in a controlled environment. Molecular manufacturing might actually be a lot like farming!

Figure 1.1.3

The number of nano-papers in different fields. The decrease within materials science and engineering can be attributed to the increase in interdisciplinary research. Increased activity within life sciences is not (yet?) observed. The physical sciences are actually underestimated because the search did not include explicit search terms in the area of scanning probes. Data taken from [Meyer, 1998b]



Finally, the clustering process of enabling techniques from the various disciplines in itself is an interesting case for scientists in the field of science policy [Meyer, 1998; Meyer, 1998b]. Figure 1.1.3 shows how the exponential increase in the number of nano-papers is differentiated over various fields.

The birth of molecular nanotechnology would not mean the end of physics, chemistry and biology. These disciplines will continue to study nature but merge in this new multidisciplinary field, especially while developing applications. Another reason for their continuation is that – roughly speaking! – they tend to focus on different atoms: inorganic elements like silicon and metals are mainly studied by inorganic chemistry and physics, organic chemistry requires the presence of carbon besides oxygen and hydrogen, and biotechnology tends to work with materials containing nitrogen as well as carbon. Molecular nanotechnology will lead to all kinds of architectures, containing all kinds of combinations of all atoms in the periodic system, but the nature of the atoms themselves will of course never be changed by this.

Nanotechnology today

The new field of nanoscale science and technology has become more and more visible over the last few years. However, it is not a single field. The most important distinct areas are nanoelectronics, nanomaterials, molecular nanotechnology and nanoscale-resolution microscopes. This is a practical classification based on emerging clusters of enabling technologies (table 1.1.1). These fields also have clear characteristics in terms of technological maturity and industrial importance.

Nanoelectronics is the driving force behind the current development of nanotechnology. In fact, this leads to a one-sidedness that threatens the interdisciplinary development. An enormous market pull induces the microelectronics industry to continue the current trend of miniaturization down to the nanoscale

field	description	enabling technologies	chapter
nanoelectronics	nanostructuring of surfaces	lithography (including scanning probes), controlled self-assembly	2
nanomaterials	nanoparticles and nanostructured materials	various synthesis, characterization and processing techniques	3
molecular nanotechnology	bottom-up synthesis with molecular precision	supramolecular chemistry, molecular association, biomolecular chemistry	4
nanoscale-resolution microscopes	characterization of nanostructures	scanning tunneling microscopy, atomic force microscopy, optical microscopy	5

Table 1.1.1
The most important fields of nanotechnology today.

(section 2.2.1). The area of *nanomaterials* contains numerous proven technologies on a lab scale. Although major existing industries are hesitant to develop these into commercial applications, the nanomaterials industry is growing. *Molecular nanotechnology* is still in its infancy: it is largely science. And finally, a strong high-tech industry has rapidly developed behind *nanoscale-resolution microscopes* because of their usefulness as a tool for the analysis. They also have demonstrated potential for high-density data storage; their use for atomic manipulation (synthesis) is still pure science.

Other areas such as high-precision engineering and microsystem technology are not addressed in this study. High-precision engineering seems to be following a route on its own into the nanometer range [Malsch, 1997b], while the STT Study Center for Technology Trends treated microsystems previously in a separate study project [Klein Lebbink, 1994].

These four fields have provided a useful framework and are treated in the separate chapters 2 to 5 of this book. Each chapter is the joined effort of a task force of experts in the various fields (see survey organization at the end of this book). It should be recognized however, that these fields are not fully independent either. For a start, the border between nanomaterials and molecular nanotechnology is somewhat fuzzy, especially for the fields of polymer chemistry (section 3.8) and food technology (section 4.1). Moreover, some of the more spectacular examples (section 1.2) of nanotechnology refuse to fit into one of the four categories. For example, nanoscale-resolution microscopes can be used for surface modification in the fabrication of nanoelectronics (section 2.2.4). And if their ability for atomic manipulation (section 5.2) could be improved, they might develop into assemblers: molecular nanotechnology. The emerging field of molecular electronics is the application of molecular nanotechnology for nanoelectronics.

The impact of nanotechnology

The impact of new technologies on society can be viewed as coming in ‘waves’ [Toffler, 1980]. Nanotechnology is still in its infancy and concerted research efforts are needed before the full potential can be realized [Crawford, 1998]. When this happens, it will form the next wave after solid-state technology and biotechnology (figure 1.1.4). The nature of its impact is determined by the general notion that control over the arrangement of atoms creates new possibilities for manufacturing. Nanotechnology is considered a key technology for the 21st century for two reasons:

- 1 since all manufactured products consist of atoms, all product areas will eventually be affected;
- 2 some futurologists expect that the development of molecular assemblers will revolutionize production, thereby altering our economic structure in the so-called ‘diamond age’. However, this study project forms no support for this expectation.

These two issues will be discussed below.

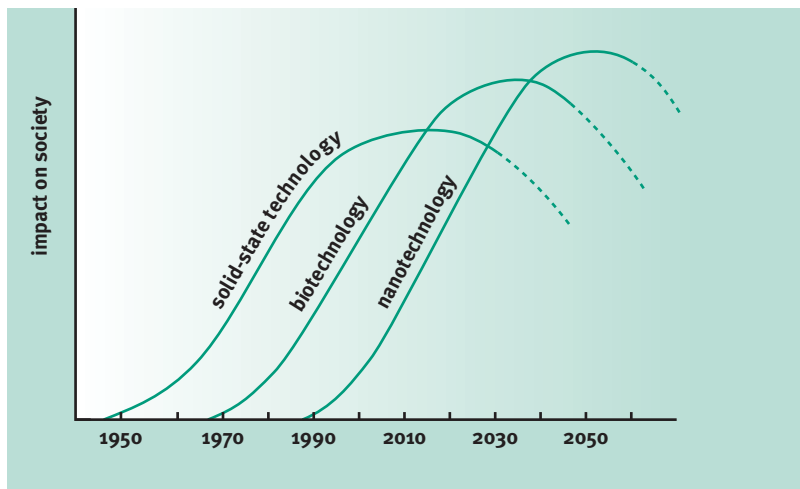
Opportunities for new products arise from properties otherwise unattainable, more functions, greater complexity and homogeneity, large surface areas and information densities, etc. The various chapters contain many examples. They roughly fall into three distinct categories:

- Electronics* faster computers and memories with higher storage densities (chapter 2);
- Materials* nanostructuring leads the way to materials with new or improved properties, with applications in various other areas such as (opto)-electronics, catalysts, cosmetics and skin care, pigments, coatings, optics, energy technologies, the automobile industry, sensors, improved cutting tools, high performance parts for the aerospace and the building industry, and packaging foils (chapter 3);
- Medicine* for instance DNA-chips (section 1.2), drug delivery systems (section 4.6) and biocompatible materials.

The development of commercially viable near-term applications besides nano-electronics is important for the interdisciplinary development of nanotechnology. The really tough question is: in what order will the various product areas be affected, and how far-reaching will the implications be?

A (pretty general) answer is presented below.

Figure 1.1.4
Waves of technology affecting society.



Now

In fact, many high-tech applications in daily life already contain simple nanostructures such as thin films. Two ordinary examples: nanometer-thin coatings on surfaces are common, and diode lasers are based on nanometer-thin films called quantum wells. A more spectacular example is the biochip array (section 1.2).

Soon

The near-field scanning optical microscope may be commercialized as a high-density data storage device as soon as 1998 (section 1.2). Nanomaterials have a

demonstrated potential to yield commercial products such as scratch-resistant plastic glasses, nanostructured solar cells, smart windows, superplastic ceramics and many others (section 3.10) within five to ten years. The production processes require upscaling, with attention to health and safety aspects. The semiconductor industry plans to produce commercial chips containing 100-nm features by the year 2006, beginning the era of commercial nanoelectronics. Molecular nanotechnology promises drug- and DNA carrying liposomes, new biosensors and materials within 10 or 20 years.

Probably at some time

Molecular electronics, biochips, artificial intelligence, better or smarter conductors (for heat, electricity, sound, light or molecules), self-cleaning textile [Forrest, 1995], frictionless bearings, wearless surfaces, improved or artificial food designed by molecular nanotechnology, biocompatible electronic implants, highly specific delivery systems using artificial nanostructures with adjusted degradation (life switches) as drug- or DNA-vectors into the cell, highly specific drugs, molecular machines, molecular assemblers, etc.

Maybe, if ever: the diamond age

A future with almost universal molecular assemblers such as first predicted (and preached) by futurologist K. Eric Drexler would bring about a revolution in fabrication technology and might lead humanity into the 'diamond age' [Drexler, 1991]. Diamond, a particular arrangement of carbon atoms, is the stiffest material around. A 'molecular factory' of dedicated molecular assemblers could produce it in large quantities at very low costs [Drexler, 1992]. Just as the Stone Age, the Bronze Age, and the Steel Age were named after the materials that humans could make, the epoch of molecular nanotechnology is commonly referred to as the Diamond Age [Merkle, 1997b]. The implications of this possible future scenario are far-reaching and surprising, even shocking. For instance, the ease of production of any imaginable material structure would completely turn over our economic structure. Matter would be as software: the cost of manufacturing additional copies of a product would become much lower [Ellenbogen, 1997]. Hence being poor or rich would depend on your imagination only: a true economy of ideas. However, even this situation might not last if computers with superhuman, truly creative intelligence outsmart us. It is conceivable that self-reproducing molecular factories will be developed; these would be truly artificial life forms, comparable to an organic cell but based on different principles and molecules. Bio- and nanotechnology combined might suffice to improve our genetic makeup and to repair our bodies using nanorobots until the brain becomes truly dysfunctional. Before this happens, we might consider 'uploading' our conscience into a computer by making a cell-by-cell copy of our brain, including all connections.... Or not, because this is the realm of science fiction and of the

transhumanists³ or extropians, who intend to improve the human race beyond its natural capabilities. In how far this scenario is realistic and desirable is a tough question. Right now, no one can prove that it is impossible, since it seems that no physical laws are violated. Hence molecular manufacturing of macroscopic products using Drexler's nanomachines could be realized. However, the drastic reduction of manufacturing cost required for a revolution of our economic structure is not foreseen by STT. The molecular manufacturing industry is more likely to have characteristics of both agriculture and the chemical process industry, with only moderate cost reductions due to the need to control feed-stock and process conditions.

Ethical objections will resemble those against biotechnology. Whereas biotechnology can produce modified living organisms, molecular nanotechnology might be able to modify the concept of life itself.

Nanotechnology for sustainability

Just as any technology, nanotechnology can be used for good or for bad. In fact, there is an ultimate doom scenario called the 'grey goo' in which *all* matter on earth is transformed into copies of the grey-goo virus. Nanotechnology will definitely be used to build more powerful weapons, first of all by using nanoelectronics and nanomaterials. This is by no means a reason to try and 'stop' the development of nanotechnology, since this would mean the end of science. If, on the other hand, it proves possible to synthesize malignant artificial viruses using molecular nanotechnology, it would be advisable to set up international treaties to banish this type of nanotechnological warfare.

On the other hand, nanotechnology also promises to become a key technology for the development of a sustainable society [Smalley, 1995]. This can be illustrated by some examples. Ultra light materials lead to material saving. The value of organic solar cells, improved batteries, fuel cells and better insulation materials is obvious. Better sensors, filters, membranes and improved catalysts offer possibilities for, e.g., the process industry to improve the process efficiency and to reduce the residue. Pigments based on nanotechnology are already commercially available; new water-soluble paints would reduce the environmental impact compared with aromatic solvents. If nanotechnology evolves into a technology with far-reaching control over matter during the next century, a high level of sustainability may also be reached for the use of materials. In theory, the materials chain can even be closed. Residue can be broken down to the desired molecular building blocks by means of so-called disassemblers. A disassembler can be an advanced catalyst, but also a benign artificial virus. The molecular building blocks can subsequently be rearranged into new products in a 'matter compiler'. Finally, diamond, as promised by molecular nanotechnology, is also a highly renewable material.

.....
3 <http://www.dse.nl/~transced/eindex.htm>
(Transcedo, Dutch Transhumanist Society)

1.2 RECENT BREAKTHROUGHS IN NANOTECHNOLOGY

This section presents several spectacular examples of today's nanoscale science and technology. In fact, top scientific journals such as *Nature* or *Science* report fascinating scientific results in this area at least once a month; this is only a top selection. Due to their innovative character, some examples fit in more than one field of nanotechnology, which is why we present them case by case.

A self-assembling electronic connection

With continued miniaturization, the features of electronic circuits will eventually become so small that top-down nanofabrication will be both impractical and very expensive (chapter 2). Scientists in Haifa, Israel, have recently shown for the first time that it is possible to use a bottom-up technique called molecular self-assembly (section 4.2) to fabricate an electronic connection [Braun, 1998; see also Molnar, 1998]. Two gold electrodes were placed 12 to 16 μm apart on a non-conducting surface. The electrodes were each marked by coating them with specific but different oligonucleotides (short DNA chains). The electrodes are covered with an aqueous solution containing DNA molecules with 'sticky ends' attached to each side with a preference for the coating on one of the electrodes. The solution is flowing so that the molecules are oriented along the direction of the gap between the electrodes. The ends of each DNA molecule flowing across the gap 'look for' the gold electrodes. Half of the molecules is oriented the wrong way, while most others are washed away before they can establish a connection. However, after some time, usually a few minutes, a DNA molecule bridges the gap to form a 'spontaneous' connection. This is observed by fluorescence microscopy, after which the flow is terminated. The DNA wire is made electrically conducting by covering it with silver. Fabricating even smaller structures is certainly possible.

20 gigabyte on a 3.5-inch disk

Two American companies, TeraStor⁴ and Quantum⁵, have developed a new removable storage medium with a density surpassing the current optical disks by a factor of ten and comparable to that of current hard disks [Raaijmakers, 1998]. In erasable cd-rom and magneto-optic (MO) drives, the size of a bit is fundamentally limited by the diffraction limit. The way to push or even circumvent this limit is to use a near-field optical microscope (section 5.4). The companies have developed a read/write head based on the ones used in hard disk drives today, but modified to work with optical principles. The enhanced head carries a set of lenses, including a special type known as a solid immersion lens (SIL). This lens is positioned so close to the disk surface that it acts like a magnifying glass lying on a newspaper. A bit of information is written by applying a focused light pulse with sufficient energy to heat the magnetic material above the

⁴ <http://www.terastor.com/>
⁵ <http://www.quantum.com/products/optical/questions.html>

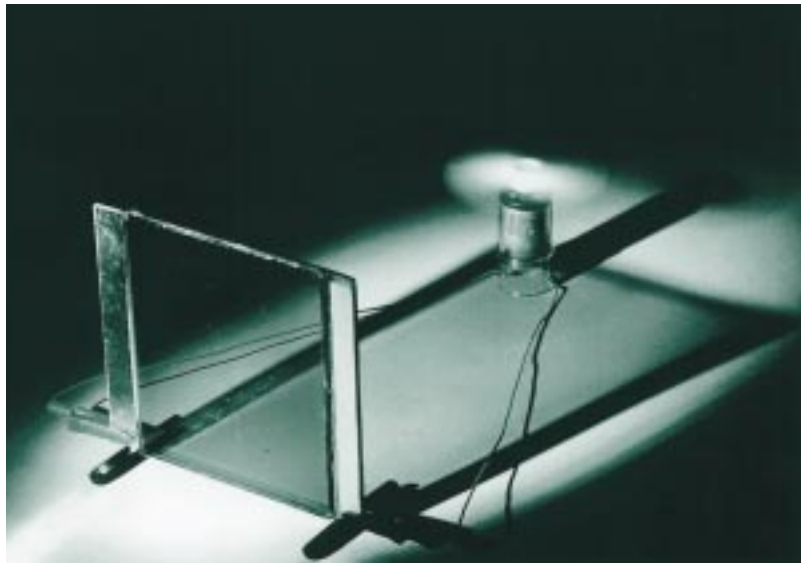
so-called Curie temperature. This makes the material susceptible to external fields. A miniature electromagnet – integrated into the head – changes the orientation of the magnetization within the illuminated area. The magnetization can be detected using polarized light. The solid immersion lens enables focusing of the laser light to a smaller spot, thereby allowing a much higher storage density. TeraStor and Quantum have announced the market introduction of removable 3.5-inch disks with a storage capacity of 20 gigabyte (Gb) in 1998. Target applications are backup, archiving, video capture and editing, and high performance graphics. The capacity is expected to double soon after with the next generation of products. Experiments indicate the possibility to achieve 100 Gb/in² at a readout speed faster than 1 Mb/s [Hosaka, 1997].

A nanostructured solar cell

The Swiss scientist Grätzel has created a technical breakthrough by the development of a so-called ‘organic’ solar cell using nanostructured titanium dioxide (TiO₂) material (figure 1.2.1) [O’Regan, 1991]. It is called organic because the cell is made light-sensitive by using an organic dye (ruthenium complexes).

Figure 1.2.1

Demonstration of the Grätzel cell⁶. The light falling on a plate of nanostructured, dye-sensitized material (left) generates a voltage difference between the two electrodes; the resulting electric current sets a propeller in motion. Courtesy of M. Grätzel, École Polytechnique Fédérale de Lausanne, Chemistry Department, Switzerland



The dye molecules are chemically attached to the titanium dioxide. After excitation by a photon, the dye molecule ejects an electron into the material: this is the necessary charge separation that generates current through any photoelectric device. The electron travels through the porous material towards the anode (figure 4.9.1). The current cycle is completed by regeneration of the dye. The best Grätzel cell has an efficiency of 10 to 12% [Goossens, 1997]. The main ‘trick’ is that a porous nanostructured material has an enormous ‘internal’ surface area. This, together with the idea of coating this area with an absorbing dye, is

⁶ <http://dcwww.epfl.ch/icp/ICP-2/solarcell.html>

responsible for the high yield that potentially makes them serious competitors of silicon solar cells. Efficiencies of the organic solar cell are comparable to silicon-based photovoltaic cells, while their manufacturing costs are anticipated to be much lower. The Grätzel cell still has a few practical limitations; a Dutch consortium has developed a modified version for which the industry has shown interest.

Hybrid materials (section 3.3)

Hybrid materials are constructed from a combination of inorganic and organic components that are chemically connected on a molecular level. They are very suitable for application as coatings on various substrates. For instance, coatings that are flexible, transparent, and resistant to scratches, abrasion, or chemical attack, can be obtained on soft plastics by the incorporation of preformed nanoparticles of silica and metal oxides. This offers opportunities both to replace glass with the much lighter polycarbonate – especially in ophthalmic glasses, head lights and car windows – and replace soft plastics with a material equipped with a hard protective coating. An example of the strengthening of plastic by a scratch- and abrasion-resistant hybrid coating on polycarbonate is shown in figure 3.3.4: the uncoated half of a test sample clearly shows the effects of wear, while the coated part is not visibly affected.

DNA chips [SRA International, 1997]

Affymetrix⁷, an American company in Santa Clara, California, introduced the first commercial ‘DNA chip’, the GeneChip, in 1996 (figure 1.2.2). It is the DNA equivalent of the so-called lab-on-a-chip approach. GeneChips contain thousands of DNA probes, each with a different nucleotide sequence, which can detect active genes when diced genes from a human cell are poured over the chip. DNA chips represent a major breakthrough: they can already decode genes 10 to 100 times faster than conventional technology, and they are improving rapidly.

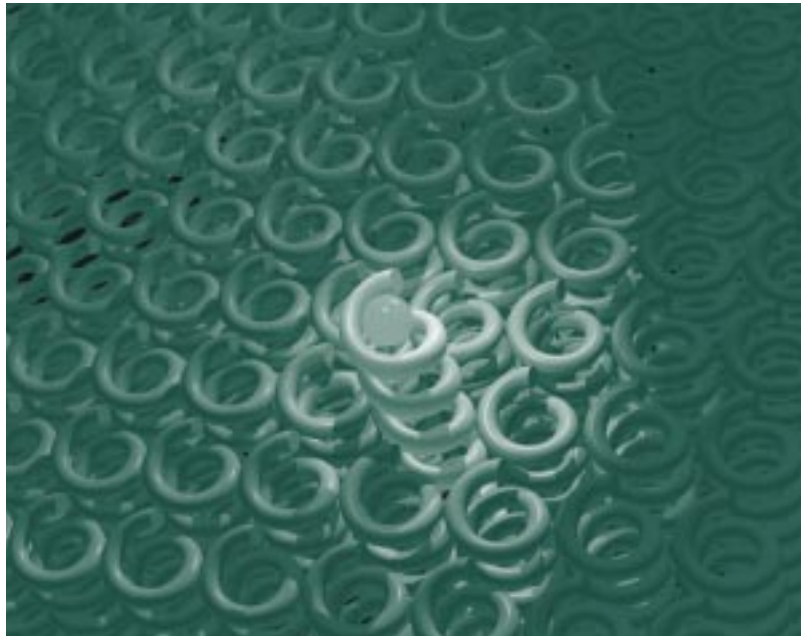
Strictly speaking, the current generation of GeneChips is not a product of nanotechnology. The chips’ smallest features have dimensions of tens of microns and their design approach borrows heavily from the current semiconductor industry. Rather, the GeneChip is a highly innovative combination of microelectronics and biotechnology. It shows the power of an interdisciplinary approach and gives a foretaste of what can be achieved by nanotechnology in twenty years time. GeneChips are actually evolving according to Moore’s Law, which posits that the power of computer chips doubles every 18 months. The number of DNA probes on Affymetrix’s prototype chips has increased from 20,000 in 1994 to 65,000 in 1996 and 400,000 in July 1997. It is only a matter of time before the probe size is reduced to 100 nm (the requirement for nanoelectronics) and ultimately to a single molecule (the requirement for molecular nanotechnology).

7 <http://www.affymetrix.com>

The current GeneChips are already being used to determine what genetic malfunctions are associated with particular diseases. This new knowledge will sweep aside traditional disease categories. DNA chips are also being used as diagnostic devices. For example, 500 genes have been found to alter when prostate cells turn cancerous, and chips can be designed to test for the presence of those alterations. Today, blood tests are available that can reveal whether a person harbors aberrant genes that increase the risk of getting colon cancer or melanoma, or brain diseases such as Alzheimer's disease. Tests for genetic predisposition to dozens of other diseases are currently being tested in research studies, and many of them will enter the market over the next few years.

Figure 1.2.2

Artist's impression of a DNA chip. The Affymetrix chip contains 16,000 different cells of $93 \times 93 \mu\text{m}^2$. Every cell contains millions of identical oligonucleotide molecules that function as a gene probe. These molecules are applied using lithographic techniques similar to those used in the microelectronic industry. When a liquid containing diced genes from a human cell is poured over the chip, gene pieces whose sequence corresponds to that of a particular cell will mate to that oligonucleotide. Under a laser light, the probes that have found a match will glow. The location of glowing dots on the chip is detected using an optical microscope, and reveals which genes are present. For a color print of this figure see page 328.



DNA chips will make individual genetic profiling, or genotyping, possible at reasonable costs. Within 10 to 20 years it will be possible to put a few of your cells on a DNA chip scanner and quickly test for subsets of scores of different diseases. Looking ahead 20 to 30 years, it may be possible to build a 'human model on a chip', a chip with DNA representing all of the approximately 100,000 human genes, which could characterize a broad spectrum of diseases. Besides health care, DNA chips will influence other fields using recombinant DNA technology. Two institutes in Wageningen, the Netherlands, have recently founded the 'Gene Expression Center' for research on the role of genes that are involved in the biosynthesis of various substances in plants for both food and non-food products. Although Affymetrix is the first company to introduce a commercial chip, the technology seems so lucrative that a host of companies are already positioning themselves to become the 'Intel' of DNA chips.

Designed protein pores as components for biosensors [Braha, 1997]

One of the first expected products of molecular nanotechnology is a protein-based molecular sensor. There is a pressing need for new sensors that can detect a variety of substances, ranging from simple ions to complex compounds and even microorganisms. The devices should offer sensitivity, speed, reversibility and selectivity. Given these criteria, protein pores in lipid bilayers (formed by self assembly) are excellent prospects as components of biosensors. It is possible to measure the conductance of an individual pore. Moreover, the proteins can be remodeled so that their transmembrane conductances are modulated by the association of specific substances.

Recently, engineered protein pores have been developed and used to detect various atoms in nanomolar concentrations. A modified form of a bacterial pore-forming protein (staphylococcal α -hemolysin) was obtained by structure-based design and chemical modification of one subunit. This subunit contained a binding site for a divalent metal ion. Nanomolar concentrations of divalent zinc (Zn(II)) produced a detectable change in the electric current of a single protein pore. Other divalent metal ions modulated the current and produced characteristic signatures. In addition, modified proteins containing more than one mutant subunit exhibited distinct responses to divalent metal ions. Hence, a large collection of responsive pores can be generated through subunit diversity and combinatorial assembly. In addition to the nanomolar sensitivity, the engineered pores have several advantages as potential sensor elements: the binding of substances to be analyzed is rapid and reversible; strictly selective binding is not required because single-channel recordings are rich in information; and a single sensor element might be used to quantitate more than one substance at once. The approach can be generalized for additional substances.

1.3 INTERNATIONAL SITUATION

1.3.1 OTHER NANOTECHNOLOGY FORESIGHT STUDIES

Both before and during the STT study⁸ (1996-1998) [NanoTechnology Magazine, 1997], several other nanotechnology foresight studies were performed, such as a German Delphi study [BMBF, 1993-1995], an early European inventory [Tolles, 1994], and a Japanese comparative foresight study [NISTEP, 1994]. The North American RAND Corporation has concluded an inventory study aimed at the USA [Nelson, 1995]. One of the recommendations was the appointment of a coordinator for national science programs. Indeed the National Science Foundation (NSF) has appointed professor Mike C. Roco for this purpose (section 1.3.4). The steering committee of the Scientific and Technological Options Assessment (STOA) of the European Parliament has done the same for nanotechnology in the broad sense in Europe [Malsch, 1996; Keith, 1996; Garrelfs, 1996], and the Netherlands Foresight Steering Committee for Science and Technology (OCV) has performed a study for the Dutch government [Garrelfs, 1995]. The European Institute for Prospective Technological Studies (IPTS) has concluded a study project on the innovation potential and societal aspects of nanotechnology, that was synchronized with the STT study project [Malsch, 1997b].

These reports expect nanotechnology to become more and more important over the next 20 years. They also state that several nanotechniques already allow for the development of commercially interesting products. The latter observation, in particular, formed one of the motivations for initiating the STT study project. Most reports recommend more detailed assessments of nanotechnology. In fact, the Society of German Engineers (VDI) had already performed a thorough nanotechnology foresight study on nanophysics and nanochemistry [Bachmann, 1994].

Interesting recent literature is a study on applications [Mayer, 1996], an English report [POST, 1996], a study by the United Nations Industrial Development Organization [UNIDO, 1997] a brochure by the German science ministry (in German) [BMBF, 1998], and a 50-page internet text document presenting an overview of the entire field [Howie, 1997]. Finally, in Japan, Hari Singh Nalwa of Hitachi Research Laboratory is compiling a 3000-page book entitled Handbook of nanostructured materials and nanotechnology [Nalwa, 1996].

⁸ http://www.stt.nl/_privateE/hpnan.htm

1.3.2 NANOTECHNOLOGY IN EUROPE

European Commission

Since 1992, PHANTOMS (Physics And Technology Of Mesoscopic Systems) deals with the area of nanoelectronics. Because the nanoscale lies in between the microscopic and the atomic scale, it is also referred to as the mesoscopic domain (meso = Greek for middle). This network is funded by the European Strategic Programme for Research and development in Information Technologies (ESPRIT) of the European Commission, and coordinated from the IMEC Centre for microelectronics in Belgium. Another nano-related network under ESPRIT is the NEOME Network of Excellence on Organic Materials for Electronics, that has been active since 1992.

Since 1984, research and technological development activities in the European Community have been defined and implemented by a series of multiannual framework programs. The current 4th framework program expires at the end of 1998. The internet database⁹ of the European Commission produces hundreds of relevant hits in response to the keyword 'nano'. Only the research program for materials (BRITE/EURAM) of framework 3 and 4 indicate explicit attention to nanotechnology in the context of production technologies for future industries. However, scattered over virtually all research programs, hundreds of projects concerning specific areas of nanotechnology come forward. For instance, the Advanced Research Initiative in Micro-electronics (ARI-MEL) is aimed at the development of new technologies for further miniaturization of integrated circuits. Since 1997, the BIOTECH program (biotechnology) is supporting the Structural Biology Industrial Platform (SBIP) network.

The European Commission has recently finalized the 5th framework program (1998 to 2002). The STOA report and the IPTS project were initiated by the European Parliament to investigate if, and in what way, nanotechnology should be stimulated in the 5th framework. The interim results of the internal discussion are that (1) nanotechnology remains supported but scattered over different 'actions' within the four new 'thematic programs', and that (2) the need for coordination is at least recognized. Increased or at least continued support is considered for the research programs for materials, biotechnology, electronics and energy. Coordination is considered both between the European programs and with national programs, for instance through COST¹⁰ (European Cooperation in the field of Scientific and Technical Research). COST, a framework for the coordination of national research on a European level, is already giving relatively focused attention to nanoscience. Several of the 95 different COST Actions give attention to nanoscale science and technology, such as 'Supramolecular chemistry' (1998 to 2003) and 'Nanostructured materials'. The latter has come forward from the European Consortium for NanoMaterials (ECNM) network that had been coordinated from Switzerland since 1996, with a strong input from the

⁹ <http://www.cordis.lu>

¹⁰ <http://www.cordis.lu/cost/home.html>

Netherlands. Moreover, the ad-hoc working group ‘Nanosciences’ is fully dedicated to the subject. However, it has no real mandate. Following the example of the American National Science Foundation (NSF, section 1.3.4), the appointment of a *coordinator of nanotechnology* concerning all activities of the European Commission, would probably be much more effective.

Finally, the current Training of Mobility of Researchers (TMR) scheme actually funds dozens of European networks that are working in some area of nanotechnology [Malsch, 1996]. One example is the NanoSNOM¹¹ network on (Scanning) Near-field Optics for Nanotechnology. Some of the specific programs and budgets have been summarized in table 1.3.1.

Table 1.3.1

Some of the specific programs of the European Commission and estimated budgets.

The budget information was collected in August 1996.

Source: [Malsch, 1998]

program name	estimated budgets (\$ millions)	period
ARI-MEL (Electronics)	17	3 years
BRITE/EURAM (Materials)	8	3 years
BIOMED (Biomedical Technologies)	5	3 years
BIOTECH (biotechnology; structural biology)	10	3 years
Joint Research Centre	0.8	1996
TMR (Training and Mobility of Researchers)	substantial	
ENV2C (Environment)	minor	
JOULE/THERMIE (Energy)	minor	
CRAFT for SMEs (small and medium enterprises)	minor	

Other European networks

The increase in nanotechnology-related activity in Europe is actually most apparent from the formation of several networks of scientists from universities, independent research institutes and industries [Malsch, 1997]. They are mainly organizing meetings and publishing newsletters. An example is the European Society for Precision Engineering and Nanotechnology (EuSPEN). The NANO-network from the European Science Foundation (NANO-ESF) has been coordinated from Delft and Duisburg since 1995, and focuses on materials [Fissan, 1998].

A Danish conference initiated by BioSoft originally aimed at the foundation of a European Nanotechnology Institute [Hundrup, 1996]. Since then, BioSoft and various other organizations have formed a broader consortium. They have decided to use a series of three Euro-conferences in 1998, 1999 and 2000 on the subject ‘Nanoscience for Nanotechnologies’ to establish improved coordination between different fields of nanoscience and a better integration of networks around specific themes. The conferences are organized by the Danish Center for Interdisciplinary Studies of Molecular Interactions (CISMI) and will result in the establishment of several working groups. The European Commission is

¹¹ <http://servex.physik.uni-ulm.de/exp/content/nanosnom/index.htm>

supporting these conferences under the TMR Program ‘Nanosciences for Nanotechnology’.

Finally, Philippe Van Nedervele¹² was appointed executive director of the Foresight Institute Europe, the European branch of Eric Drexler’s Foresight Institute, in 1998. The organization of the First ELBA-Foresight Conference on Molecular Nanotechnology, spring 1999, Rome, will be their first major European activity.

National activities

The *German* science ministry (BMBF) has recently launched a national nanotechnology program¹³ with a budget of about \$50 million over the next five years to establish five nanotechnology ‘competence centers’: ultrathin coatings, lateral nanostructures, nanoparticles and molecular architectures, ultra-precision engineering of surfaces, and nanostructure analysis. Each center will actually be a cooperative network of the best research groups throughout the country that are already active in that area. Meanwhile, the Institute for New Materials (INM) in Saarbruecken is already organizing annual meetings to inform the industry on the nanomaterials applications they have developed for several years.

In *Switzerland*, the national research program ‘Nanosciences’ was initiated in 1995. After a selection phase, research funded with the program started in 1996. At present, there are about 40 research participating groups, located at different Swiss institutions [Swiss National Science Foundation¹⁴, 1998].

In *Finland*, the Tekes Technology Development Center and the Academy of Finland started a nanotechnology program in 1997. The first phase of this program will last 3 years and has a budget of \$9 million [Anttinen, 1997].

At the initiative of *Swedish* research funding agencies, eleven interdisciplinary materials research consortia were formed in Sweden in 1990. The Nanometer Structure Consortium¹⁵ (1990 to 2000), coordinated from Lund University, is one of them [Malsch, 1997]. Within this consortium, specialists with different university affiliations are working jointly to study material structures with dimensions down to a few nanometers.

In *Italy*, Claudio Nicolini, director of the Institute of Biophysics in Genova, not only conducts research aimed at practical applications of bioorganic films for (opto)electronic devices, but is also one of the driving forces behind a national program on nanotechnology.

France has a national network called the ‘Club Nanotechnologie’, which is also one of the partners in the initiative of the EuSPEN network. The Centre National de la Recherche Scientifique (CNRS) has an ongoing interdisciplinary program called ‘Ultimatech’¹⁶, aimed at developing advanced technologies and instrumentation for making nanostructures [Malsch, 1996].

¹² <http://www.foresight.org/FI/VanNedervele.html>

¹³ <http://www.nanonet.de/>
(in German)

¹⁴ <http://www.snf.ch>

¹⁵ <http://anders.ftf.lth.se/nm/nm.html>

¹⁶ <http://www.cnrs.fr/Cnrspresse/n35a1.html>

The Institute of Nanotechnology¹⁷ has been created to foster, develop and promote nanotechnology in the UK. It is fundamentally a membership organization aimed at information exchange and dissemination. The LINK program, including the National Initiative on Nanotechnology (NION) network, is finished. Presently, the Institute of Nanotechnology is embarking on a project in conjunction with senior industrialists and researchers to identify those nanotechnologies that will affect industry over the next 5 to 10 years. This will be linked with the UK's Foresight exercise, which aims to identify the technological developments required to ensure the future success of key industrial sectors. The project was expected to be completed by Autumn 1998, and was intended to provide a guide for industrially targeted R&D.

A Hungarian report summarizes the nano-related research in *Central and Eastern Europe* (Bulgaria, Czech Republic, Hungary, Romania, and Ukraine); a new edition is in preparation [Mojzes, 1997].

The science policy office of *Belgium* has a system called 'Interuniversity poles of attraction' (IPA's or IUAPs) for selective sponsoring of collaborative research. Two of the current IUAPs concern nanoparticles: 'Supramolecular chemistry and supramolecular catalysis' and 'Reduced dimensionality systems'. In Leuven, the Interuniversity Center for Microelectronics (IMEC) performs applied research on nanoelectronics (section 2.4), while scientists at the University of Leuven work on scanning probe lithography (section 2.2.4) and on the chemical modification of surfaces.

The Netherlands has no explicit nanotechnology program. An inventory of the Dutch funding for nanotechnology-related research showed that a total of \$4.4 million per year is channeled through the most important funding organizations (table 1.3.2). The network of the STT Study Centre for Technology Trends will be continued in the form of a multidisciplinary Dutch-Flemish 'Platform Nanotechnology', to be installed with the conclusion of this study project in the fall of 1998. More important are four other developments: the presence of the NEXT¹⁸ (Nanoscale Experiments and Technology) project – a major effort directed at atomic scale fabrication and investigation of nanoelectronic devices at DIMES (Delft Institute for Micro-Electronics and Submicron technology), Delft –, the founding of a multidisciplinary top institute for Bio-Organic Materials and Devices (BiOMaDe) by the University of Groningen, and the work on supramolecular chemistry (section 4.3) and on near-field optics at the MESA-Institute of Twente University (section 5.4.2). In addition, there is an interuniversity research institute 'Supramolecular chemistry and technology' (SMCT) and a consortium for research on energy-oriented applications of nanostructured materials funded by the Netherlands agency for energy and the environment (Novem).

¹⁷ <http://www.nano.org.uk/>

¹⁸ <http://next.tn.tudelft.nl/>

Table 1.3.2

Estimated funding (\$ millions) for nanotechnology-related research carried out in the Netherlands channelled through the Dutch organization for scientific research (NWO) and the Dutch organization for technical sciences (STW).

	STW (1997)	NWO (1998)	total
nanophysics	0.5	2.1	2.6
nanochemistry	0.8	not available	0.8
nanobiosciences	–	0.8	0.8
other	0.2	–	0.2
Total	1.5	2.9	4.4

Science centers

More and more “real” science centers are being formed for work on nanoscale science and technology. We already mentioned the German Institute for New Materials (INM) and the BiOMaDe initiative in Groningen. The literature mentions the Center for Ultrastructure Research and the Ludwig Boltzmann Institute for Molecular Nanotechnology in Vienna, an interdisciplinary center in the area of self-assembly and self-organization in complex molecular systems (SOMS), and a center of excellence for supramolecular chemistry in Strasbourg (ISIS, 1996). There may be many more recent initiatives in other European countries. Still, as far as we know there is no European equivalent of the Japanese National Institute for Advanced Interdisciplinary Research (NAIR, section 1.3.3).

1.3.3 NANOTECHNOLOGY IN JAPAN

*A. ten Wolde*¹⁹

In Japan, government projects in nanostructure research are carried out under the Ministry for International Trade and Industry (MITI²⁰), the Science and Technology Agency (STA²¹), or Mombusho (the Ministry of Education, Science, and Culture). The total spending from MITI and STA on Exploratory Research for Advanced Technology (ERATO²²) projects, combined with funding from Japan’s Science and Technology Agency and attached industry money, is estimated to be \$538 million from 1985-1997 [Nelson, 1995]. Nanostructure research is occurring for the most part under MITI. The main fields of future commercial interest are biotechnology, micromachines, and artificial intelligence. At present, MITI seems to have two areas of great interest: micromachines and future computer chip technology. Most research on nanostructures is performed with the idea of developing future-generation computer chips. However, although the micromachine work primarily aims at the development of a table-top factory, a lot of work associated with nanotechnology in Europe and the U.S. is linked with micromachines in Japan. The differences in the definition of nanotechnology complicate an international comparison.

Several of MITI’s Industrial Science and Technology Frontier Program (ISTF)

19 Main source: [Sienko, 1997]

20 <http://www.miti.go.jp/>

21 <http://www.sta.go.jp/>

22 <http://www2.jst.go.jp/erato/>

existing projects fall into the class of research on future chip technology. A special player in the field is the National Institute for Advanced Interdisciplinary Research (NAIR²³), a laboratory founded in 1993 in Tsukuba (near Tokyo) which has concentrated research in ‘atom technology’, cluster science, bionic design and optical memory. MITI has brought together the (public) NAIR and the (private) Angstrom Technology Partnership to form the Joint Research Center for Atom Technology (JRCAT) and carry out the research on the manipulation of individual atoms. MITI also supports the Association of Super-Advanced Electronics Technologies (ASET) consortium and the more specialized Parallel Distributed Processing Research Consortium (PDPRC).

The Science and Technology Agency (STA) is involved in more long-term and basic science research. Since 1997, the Japan Science and Technology Corporation (JST²⁴) has coordinated many nanotechnology-related projects for the STA. Most of the research has already occurred under previous programs. Examples are the Ceramics Superplasticity project (1995-2000) under the International Cooperative Research Projects (ICORP), and ERATO projects such as the Yamamoto Quantum Fluctuation Project (1993-1998), the Takayanagi Particle Surface Project (1994-1999), work at the National Institute for Metals (NRIM) and the Institute of Physical and Chemical Research (RIKEN). A result worth mentioning is the synthesis of a triangular fullerene. The ERATO projects are now being devoted more and more to biotechnology. For instance, a new research project headed by Keiichi Namba is aimed at the study of how proton flows drive natural molecular motors.

The Research Center for Advanced Science and Technology (RCAST) is a laboratory with nanotechnology-related projects financed by Mombusho. Mombusho also supports the Scientific Research Project on Priority Area ‘Quantum Coherent Electronics: Physics and Technology’ (QCEPT).

In the private sector, NTT and Fujitsu seem to have more advanced materials fabrication systems than all of Europe. Japan’s electronic giants – such as Hitachi – as well as smaller companies are also working on quantum devices. There are several private consortia working on nanotechnology, especially the Semiconductor Industry Research Institute Japan (SIRI), the Semiconductor Leading Edge TEch., Inc. (SELETE) and the Semiconductor Technology Academic Research Center (STARC). Finally, in 1997, the Institute of Industrial Science (Seiken), together with the University of Tokyo, QCEPT and the University-Industry Joint Project on ‘Quantum Nanoelectronics’ (QNANO), organized an International Workshop on Nano-Physics and Electronics (NPE’97²⁵).

²³ <http://www.nair.go.jp/>

²⁴ <http://www.jst.go.jp/EN/>

²⁵ <http://www.iis.u-tokyo.ac.jp/~qceptweb/NPE97/>

1.3.4 NANOTECHNOLOGY RESEARCH IN THE USA

M.C. Roco²⁶

Nanotechnology, as defined for this survey in the USA, arises from the exploitation of physical, chemical and biological properties of systems that are intermediate in size between isolated atoms/molecules and bulk materials, where new and improved mechanical, optical, electric, magnetic, thermal, chemical and biological properties occur as compared to bulk behavior. It implies the ability to change and utilize structures and devices with a size range from about 0.1 nm (atomic/molecular scale) to about 100 nm. Surface and confinement-related properties play a dominant role. The upper size limit may vary as a function of materials and the targeted phenomena. It is estimated that nanotechnology is at a similar level of development as computer/information technology was in the 1950s, and that it will have a broad and fundamental effect on other technologies. The size range and particularly the new phenomena set nanotechnology apart from MEMS (micro-electrical-mechanical systems, an acronym used mostly in the USA) or MST (microsystems technologies, used in Europe). A brief overview of research programs, generic themes, strengths, and trends in the USA nanotechnology research is presented below.

Research programs

Various public and private funding agencies, large chemical, computer and pharmaceutical companies, as well as small and middle sized enterprises, provide support for precompetitive research programs on nanotechnology. Most of the supported programs are evolving out of disciplinary research programs, and only some are identified as primarily dealing with nanotechnology. The organizations indicated in table 1.3.3 sponsor basic research in this area at a level estimated at about \$115 million per year in 1997 [Roco, 1997a].

Table 1.3.3

Estimated sponsoring in US dollars of basic research in the area of nanotechnology in the USA over the year 1997

Organization	\$ (millions)
National Science Foundation (NSF)	65
Defense Advanced Research Projects Agency (DARPA)	10
Other defense related agencies, including the Office of Naval Research (ONR), the Army Research Office (ARO) and the Air Force Office of Scientific Research (AFOSR)	22
Department of Energy (DOE)	7
National Institute of Health (NIH)	5
National Institute of Standards and Technology (NIST)	4
National Aeronautics and Space Administration (NASA)	3
Total	116

²⁶ National Science Foundation (NSF), and Coordinator of the Nanotechnology Group, Arlington, Virginia, USA, mroco@nsf.gov.

Note: The opinions expressed in this section are not necessarily those of NSF.

The National Science Foundation (NSF) has a new initiative on functional nanostructures with a budget exceeding \$13 million in 1998. Large multinational companies, such as Dow, DuPont, Eastman Kodak, Hewlett Packard, Hughes Electronics, Lucent, Motorola, Texas Instruments, and Xerox, have established specialized groups in their long-term research laboratories for which the total precompetitive research expenditure for nanotechnology is estimated to be comparable to the corresponding government funding. Small business enterprises, such as Aerochem Research Laboratory, Nanodyne, and Particle Technology, Inc., have generated an innovative competitive environment in various technological areas including dispersions, coatings, structural materials, filtration, nanoparticle manufacturing processes and functional nanostructures (sensors, electronic devices). A series of interdisciplinary centers with focus on nanotechnology have been established in the last few years at universities, creating a much needed, growing public research and education infrastructure for this field. Examples are the University of Illinois at Urbana (including the Engineering Research Center on Microelectronics in collaboration with the Beckman Institute – a private foundation), Brown University (the Material Research Science and Engineering Center), University of Washington (with a focus on nanobiotechnology), the Richard Smalley's Center for Nanoscale Science and Technology (CNST) at Rice University, University of Wisconsin at Madison (with focus on nanostructured materials), University of North Carolina, Rensselaer Polytechnic Institute, the nanoelectronics facilities at the University of California – Berkeley and University of Texas – Austin. The National Nanofabrication User Networks (NNUN) sponsored by NSF is organized around five universities, at Cornell, Stanford, UCSB, Penn State and Howard, and its initial focus has been on nanoelectronics, optoelectronics, and electro-mechanical systems. Another national facility is the Center for Quantized Electronic Structures (QUEST) at the UCSB, with expertise on the underlying physics and chemistry aspects.

Research themes

Current interest in nanotechnology is broad-based; however, there are several generic research themes that have received more attention:

- Nanomaterials research, including synthesis, processing, properties, characterization, and utilization of nanostructured materials. This includes modeling and simulation for structure growth at molecular and mesoscopic levels, chemistry and bio-assembling techniques, artificially structured materials, and nanodevice applications. Engineering of materials with significantly improved properties through the controlled synthesis and assembly of the material at the nanoscale level is a main objective.

- Thermal spray processing and chemistry-based techniques for depositing multilayered nanostructured coatings and processing of nanoscale powders into bulk structures and coatings.
- Nanomaterials for energy-related applications, catalysis, optoelectronics and soft magnets.
- Nanofabrication, with particular focus on electronic industry and sensors. It includes development of technologies seeking speed, density, power and functionality beyond that achieved by simply scaling transistors; operation at room temperature; use of quantum wells electronic devices; and computational nanotechnology.
- Miniaturization of spacecraft systems.
- Macromolecules and self-assembling techniques: biomimetics ('taking good designs from nature'), smart structures, microdevices for telemedicine, compact power sources, lattices of nanoscale structures and Buckminsterfullerene (bucky balls).
- Neural communication and chip technologies for biochemical applications and sensor development.
- Metrology activities for thermal and mechanical properties, magnetism, micromagnetic modeling and thermodynamics of nanostructures. Nanoprobes to study nanometer material structures and devices with nanometer accuracy and picosecond time resolution have been developed.
- Metallic, ceramic and polymeric nanoparticle, cluster, crystal, tubes and other precursors for nanostructures.

In the long term, the building-up approach from molecules and nanoprecursors (nanoparticles/nanotubes/nanolayers) to generate nanostructures under controlled conditions is the most promising avenue for scientific research, innovations and industrial relevance. The scaling-down approach to nanoscale and materials restructuring, however, will also continue to be used.

Previous NSF activities include

- the Advanced Materials and Processing Program, with a focus on nanostructured materials;
- the Ultrafine Particle Engineering program, which focused on new concepts and fundamental research to generate nanoparticles at high rates;
- the National Nanofabrication Users Network, which connects researchers and facilities at five universities to fabricate nanometer-scale structures, and enables others to miniaturize devices and process nanodevices;
- an initiative on Instrument Development for Nano-Science and Engineering (NANO-95) for new instrumentation to advance atomic scale measurements of molecules, clusters, nanoparticles and nanostructured materials.

Research strengths have been developed in several areas: nanostructured materials with superior properties, special coatings, chemistry self-assembling techniques, and nanobiotechnology. Exploratory research include tools of quantum control and atom manipulation, artificially structured molecules and materials, biomimetics, nanoscale robotics, encoding and utilization of information by biological structures, and DNA computing. Future research work is expected to continue the following thrusts:

- expanding basic understanding of phenomena specific at nanoscale, with an increased role of biology;
- combining synthesis, assembling and utilization of nanostructures and devices into continuous processes;
- developing new nanostructures and devices with principles similar to those in the nature (biomimetics);
- developing instrumentation based on novel principles for probing properties not well understood at the nanometer scale, and
- physical, chemical and biological modeling and simulation of nanostructure growth dynamics, assembling processes at mesoscale and grain interfaces;
- using hierarchical, adaptive simulation techniques at atomic, molecular, mesoscopic, grain, and macroscopic scales.

Commercially viable technologies are already in place for some ceramic and polymeric nanoparticles, nanostructured ceramic and metallic alloys, colorants and cosmetics and electronic components such as those for media recording and hard-disk reading, to name only a few. Several applications in nanoparticle manufacturing are already established [Roco, 1997b]. The time interval from discovery to application varies in a broad range. In another example, in only several years from the discovery of a new phenomenon in nanostructures called giant magnetoresistance [Berkowitz, 1992], the corresponding technology has completely replaced the old technologies for disk computer heads in an over \$20B hard-disk market [Williams, 1998]. All disk heads in the world currently are manufactured by IBM and Hewlett Packard using this discovery or advances of it. However, most of the technology base is in development and industry cannot sustain alone the research effort necessary to create the scientific and technological infrastructure. Government funding (such as NSF and NIH in the USA) and private agencies (such as the Beckman Institute) plays this role for fundamental research. Industrial performance is affected by the infrastructure and public funding: the infrastructure for research and education in the area of nanotechnology is still in formation, while funding from governments for industrial research is limited because the market is not yet established.

Closing remarks

Nanotechnology research in the USA has been developed in open competition with other research topics within various disciplines. This is one of the reasons that the USA research efforts in nanotechnology are relatively fragmented and partially overlapping among disciplines, areas of relevance, and sources of funding. This situation has advantages in establishing competitive paths in the emerging nanotechnology field and in promoting innovative ideas, and some disadvantages in developing practical, system applications. To improve on the current situation, a Coordinating Group on Nanotechnology was established in 1997 with participants from twelve funding/research agencies. It plans to enhance communication and develop partnerships. The Group has appointed a panel of experts in the field to provide a worldwide perspective of the main research and technological issues on 'Nanoparticles, Nanostructured Materials and Nanodevices'. The results of the study were presented on Feb. 10, 1998 in a public workshop in Virginia [World Technology Evaluation Center, 1998]. A workshop for benchmarking nanotechnology research in the USA was completed in May 1997 [Siegel, 1998]. The path of revolutionary discoveries that we are witnessing now in nanotechnology is expected to accelerate in the next decade in the USA and worldwide.

1.3.5 INTERNATIONAL COMPARISON

A. ten Wolde

If nanotechnology were an Olympic event, the United States would take home the gold, Europe the silver, and Japan the bronze in spite of the seemingly impressive programs [Kaiser, 1998]. This was the conclusion of the workshop on the global assessment of nanotechnology organized in the USA in February 1998 [World Technology Evaluation Center²⁷, 1998]. The technological comparison by WTEC indicated that the USA leads in fields such as synthesizing new nanomaterials and Japan in making nanoelectronic devices, while Europe and the USA tie in crafting novel coatings (table 1.3.4). This 'picking order' is confirmed in several ways. The RAND report already listed about 119 research groups working on nanotechnology in the USA, 67 in Europe, 22 in Japan, and 7 in the rest of the world [Nelson, 1995; Howie, 1997]. A recent bibliometric analysis again confirms the conclusion for scientific papers (figure 1.3.1) and patents between 1990-1997: USA (1636)²⁸, Western Europe (245), Japan (150) and the rest of the world (22). The distribution of patents and papers in Western Europe is shown in figure 1.3.2 [Meyer, 1998b]. Only the amount of money that governments spend on nanotechnology (about \$430 million a year) shows a different picture: \$125 million in Western Europe, \$120 million in Japan (1996), \$115 million in the USA (section 1.3.4) and \$70 million in other countries [Roco, 1997a].

27 <http://itri.loyola.edu/nano/>

28 The score for the USA is relatively high due to the use of US patent data

Table 1.3.4

World leaders in nanotechnology.
 Source: World Technology Evaluation Center (WTEC²⁹), Loyola University

	gold	silver	bronze
synthesis and assembly	USA	Europe	Japan
biological approaches and applications	USA/Europe	Japan	
high surface area materials	USA	Europe	Japan
dispersions and coatings	USA/Europe	Japan	
other consolidated nanomaterials	Japan	USA/Europe	
nanoelectronic devices	Japan	Europe	USA

Figure 1.3.1

The distribution of scientific papers by region. In this graph, Western Europe includes only Germany, France, UK, Spain, and Italy; Russia counts for what used to be the Soviet Union. Duplicate country addresses have been removed. An analysis of country co-authorship showed various interesting patterns of international collaborations, that is an intended area of further study. Data taken from [Meyer, 1998b]

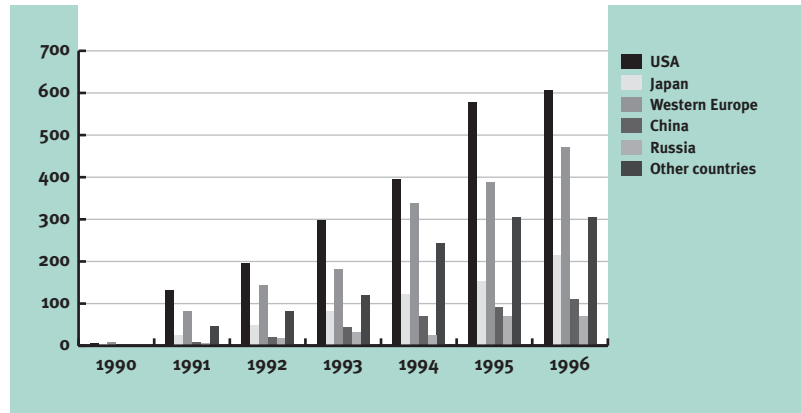
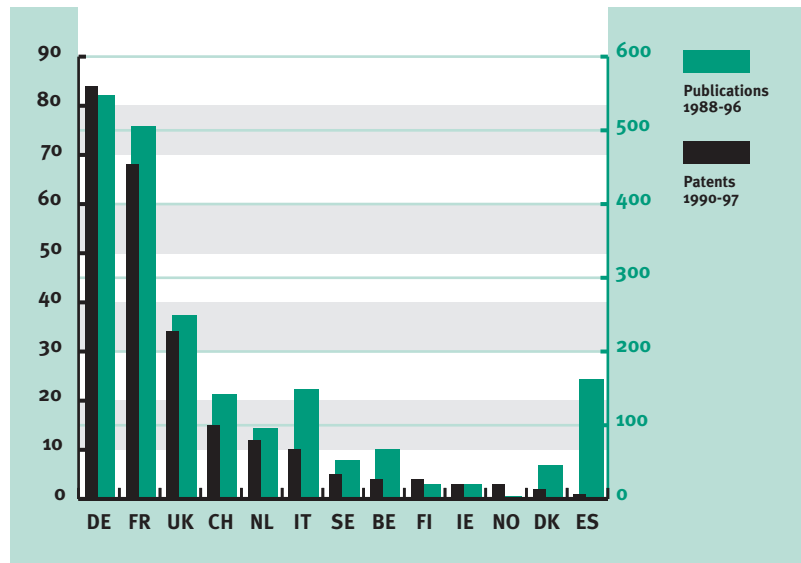


Figure 1.3.2

The number of patents and publications in different countries in Western Europe. The case of nanotechnology is used to study the relation between papers and patents in general. Data taken from: [Meyer, 1998b]

- DE = Germany
- FR = France
- UK = Great Britain
- CH = Switzerland
- NL = Netherlands
- IT = Italy
- SE = Sweden
- BE = Belgium
- FI = Finland
- IE = Ireland
- NO = Norway
- DK = Denmark
- ES = Spain



Industrial involvement

In 1995, the RAND Corporation tabulated some 200 centers of nanotechnology research worldwide. These are mainly university departments; industrial involvement is not yet comparable [Nelson, 1995]. Still, Nanothinc³⁰, a web-based nanotechnology information service, has drawn up a list some 250 ‘nanovendor’ companies across the broad range of the field. Many of these are small and medium-sized enterprises such wafer-stepper producer ASM Lithography³¹ (section 2.2.1), that are actively stimulating innovative R&D in a specific area. Of the big companies, only electronic companies can be

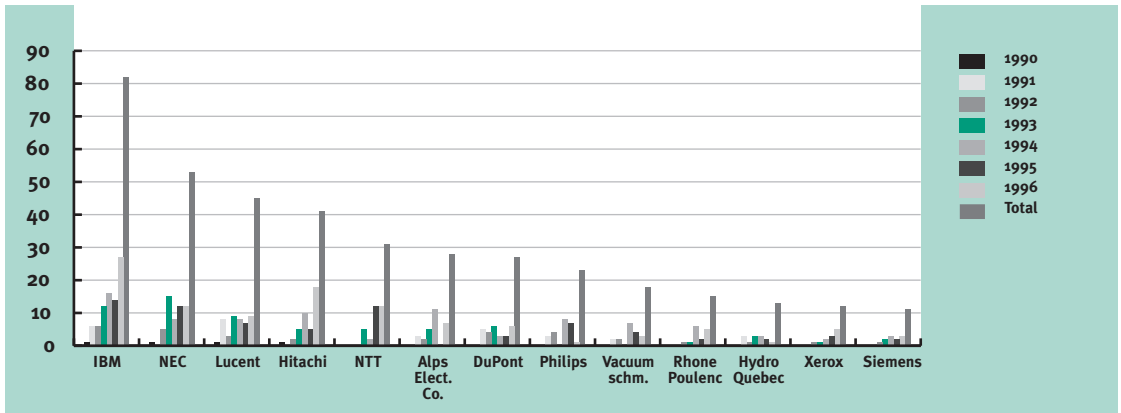


Figure 1.3.3

Companies with more than 10 papers in nano-related areas. Data taken from [Meyer, 1998]

distinguished as true leaders in the field of nanotechnology (figure 1.3.3). Of these, Philips – rather surprisingly – pulled out of most basic nanotechnology research around 1995, as can be seen from the strong reduction in the number of nano-papers produced since then. The other large industrial companies, including chemical ones such as Akzo Nobel, are more or less waiting for break-throughs.

³⁰ http://www.nanothinc.com/NanoVentures/NanoVendors_Frames/nvframes.html

³¹ <http://www.asml.nl>

1.4 ABOUT THIS BOOK

This book is the result of a nanotechnology foresight study (1996-1998) carried out with the help of 69 nanotechnologists in the Netherlands, Flanders, and abroad (see the ‘Survey organization’ at the end of this book). It presents a variety of methods for the fabrication and analysis of nanostructures. It is *not* an inventory but intends to give a broad overview of nanotechnology. The emphasis lies on the development of new enabling technologies; from these, opportunities for applications have been identified. We hope that you will be surprised by the examples of what is already possible today and what might be possible in the future.

SOURCES

Magazines

- Foresight Update³², a publication of the Foresight Institute, Palo Alto
- NanoTechnology Magazine³³ – Pre-press monthly, Hawaii
- Nanotechnology Journal, IoP Publishing³⁴, London

Television programs

- *Nanotopia*, issue on nanotechnology, BBC, Horizon, 13 November (1995)
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34 <http://www.iop.org>

35 <http://www.bbc.co.uk/horizon/solesun.shtml>

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⁴⁰ <http://keydet.sra.com/hs2020/homepage/hs2020.htm>

⁴¹ <http://www.nanozine.com>

⁴² <http://www.nistep.go.jp/achiev/report33-e/report33-e.html>

⁴³ <http://www.foresight.org/Conferences/MNT05/Papers/Sienko/index.html>

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⁴⁵ The full report can be downloaded at <http://keydet.sra.com/hs2020/homepage/hs2020.htm>

⁴⁶ <http://itri.loyola.edu/nano/views/>

2

Nanoelectronics

2.1 INTRODUCTION

A. ten Wolde

The field of nanoelectronics is the first major application area for nanotechnology. Due to the continuing trend of miniaturization of computer chips, integrated circuits with nanometer features will appear on the market within several years (section 2.2.1). However, the technology that is currently used for the commercial fabrication of microchips, optical lithography, cannot be used for the fabrication of electronic devices with nanoscale features. Several alternative lithographic techniques for the *nanostructuring of surfaces* are therefore considered (section 2.2). Molecular electronics, involving three-dimensional structuring, is discussed in chapter 4. Growth techniques can also be used to fabricate quantum wells, wires and dots (section 2.3). Section 2.4 explains how magnetic computer memories are entering the nanoregime. When nanostructures are small enough, they start to exhibit quantum mechanical behavior (section 2.5) that can form the basis for future electronic components (section 2.6). The chapter is concluded with a future outlook (section 2.7).

2.2 NANOLITHOGRAPHY

2.2.1 NANOLITHOGRAPHY FOR INTEGRATED-CIRCUIT PRODUCTION

F. Bijkerk¹, J.P.H. Benschop², S. Wittekoek²

Introduction

Ever since the invention of the transistor in 1947, and later the integration of all electronic components in a single ‘chip’, miniaturization of these devices has been an ongoing basic process. The feature size of integrated circuits has shrunk by an almost constant rate of about 30% every 3 years for the last 15 years. This trend is known as Moore’s Law (figure 2.2.1). Moore formulated his law in 1965 and revised it in 1975. Since then, the transistor density on a manufactured integrated circuit has doubled every eighteen months, while the storage capacity of dynamic random access memory (DRAM) chips has increased with a factor of four every three years. It enabled faster circuits, more complex designs, and more economical production processes. Spurred to continue this miniaturization trend, researchers continue to develop novel processes with improved quality [Wittekoek, 1994]. It is expected that minimum dimensions of integrated circuits will continue to shrink at this rate over the coming decade. Mass production of integrated circuits are therefore expected to enter the area of nanotechnology before 2006. This can be seen from the current ‘roadmap’³ of the future for the semiconductor industry (table 2.2.1). This section summarizes alternative technologies, of which one or more will be required to meet the goals pursued by industry.

Lithography is considered the key technology driver for the semiconductor industry. The industry faces several challenges for obtaining resolutions of less than 100-nm. The first challenge is to achieve consensus over the post-optical technology, which involves critical issues in mask fabrication and tool development in general for all candidate technologies. Additional challenges for nanolithography are improving the control over the critical dimensions of the transistor gate, the production of these structures with adequate overlay accuracy, process control, metrology, and cost control. Beyond a certain point, the increasing costs of miniaturization will no longer be compensated by a corresponding increase in value. However, this is not expected to take place during the next ten years. Moore’s law may remain valid for an additional 20 years, or might in theory speed up upon the introduction of bottom-up nanofabrication. Ultimately, the miniaturization is limited by the size of the atom.

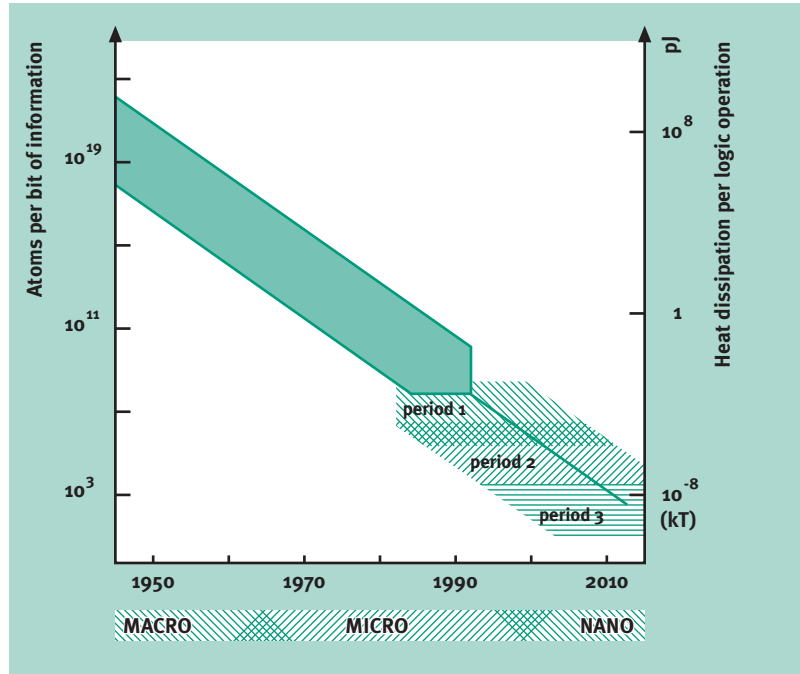
1 FOM-Institute for Plasma Physics Rijnhuizen
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2 ASM Lithography BV
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3 <http://www.sematech.org/public/roadmap>

Figure 2.2.1

Miniaturization of integrated circuits according to Moore's Law, showing the decrease in the number of atoms per bit and in the heat dissipation per logical operation. In the past two decades, miniaturization has progressed exponentially. The current challenge is to find suitable mass production methods for present-day electronic elements (period 1). After that, the challenge will be to develop new elements (period 2, section 2.6). Eventually, miniaturization will come to an end (period 3). Courtesy of H. Rohrer. Reprinted with permission from [Rohrer, 1994]. Copyright 1994 Società Italiana di Fisica.



Year of first shipment	1997	2000	2003	2006	2009	2012
<i>Minimum feature size (nm)</i>						
Dense lines (DRAM)	250	180	130	100	70	50
Isolated lines (μP gates)	200	140	100	70	50	35
Contacts and vias ⁴	280	200	140	110	80	60
Overlay ⁵ precision	85	60	45	35	25	20
Gate critical dimensions control (nm)	20	14	10	7	5	4
Storage capacity DRAM (bits)	256 M	1 G	4 G	16 G	64 G	256 G
μP (transistors / cm^2)	7 M	13 M	25 M	50 M	90 M	160 M

Table 2.2.1

Roadmap for the semiconductor industry with, amongst others, the requirement for minimum feature sizes. The minimum feature size of dense lines on direct random access memory (DRAM) chips is accepted as the 'state-of-the-art' resolution for mass fabrication. The features for isolated lines on microprocessor (μP) gates can actually be smaller. The reduced feature size implies continuing increase in storage capacities. Source: Semiconductor Industry Association, USA, 1997

4 connections between metal tracks lying on different layers

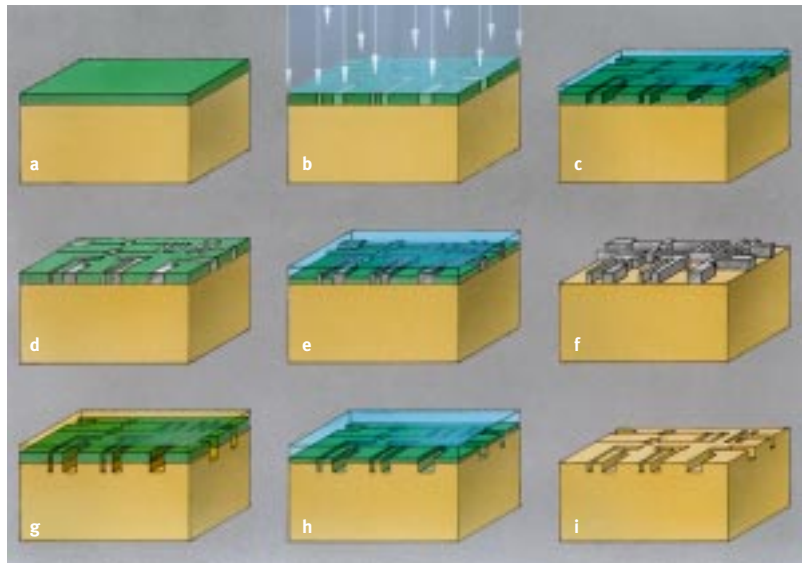
5 lateral position of one layer with respect to the next

Optical lithography

Lithography is considered to play a key role in nanoelectronics. Top-down nanofabrication involves other techniques such as etching and layering, but the lithography process defines the critical dimensions of the electronic structures that are finally the basis for operation of the circuits to their ultimate specifications. The technique ('writing with a stone') is a printing process in which the image to be printed is rendered on a silicon wafer coated with a photosensitive layer. The image is part of an electronic integrated circuit. It is transferred from a mask containing the basic patterns to the wafer by means of radiation or particles. The imaged pattern is then ready for further process steps, such as metalization or further lithographic printing. An artist's impression of a lithography process is shown in figure 2.2.2.

Figure 2.2.2

Artist's impression of a projection lithography process. (a) A silicon wafer is covered with a sensitive layer (resist). (b) A beam of radiation or particles is projected through a mask onto the wafer. The desired pattern has been transferred from the mask into dark and light areas in the beam. (c) The beam degrades this layer, so that the exposed area becomes soluble (positive resist) or, adversely, insoluble (negative resist) in a developing fluid; in this way the demagnified pattern is imaged in the resist layer. (d) The holes formed can be filled with, for example, a metal. (e) By dissolving the remaining resist layer, metal on top of the resist disappears; this procedure is known as the 'lift off' technique. (f) In the areas where the holes used to be remains a metal pattern on the wafer. (g) Alternatively, material from the layer below the resist can be selectively etched away through the holes; the remaining resist layer now functions as a protective mask during etching before it is dissolved (h). In this way, the mask pattern is transferred onto the surface itself (i). The game of deposition, projection and etching can be repeated many times to form the complex patterns of an electronic circuit.



The quality of lithographic imaging requires a trade-off between lateral (along the surface) resolution and the depth-of-focus. It is basically determined by the wavelength of the light employed, according to classical laws of optics. The lateral resolution of diffraction-limited optics is given by the following formula:

$$\text{minimum feature size} = k_1 \times \text{wavelength} / \text{numerical aperture}$$

with k_1 a system-dependent imaging constant, while the numerical aperture (NA) indicates the light acceptance angle of the optical system⁶.

Figure 2.2.3 shows the resolution as a function of the wavelength and numerical aperture for three different values of k_1 .

6 $NA = n \sin\theta$, where n is the refractive index of the lens and θ the sine of the half angle of the light cone from the lens to the image.

Figure 2.2.3

Actual and extrapolated numbers for the lateral resolution of optical lithography processes as function of the wavelength λ and numerical aperture NA for three different values of the imaging constant k_1 . This imaging constant depends upon many process parameters such as the photoresist, the source and the use of phase-shifting masks. It is currently expected that optical lithographic technology can be pushed to print features down to 100 nm as of the year 2006, but will be unable to produce nanoelectronics. Source: ASML.

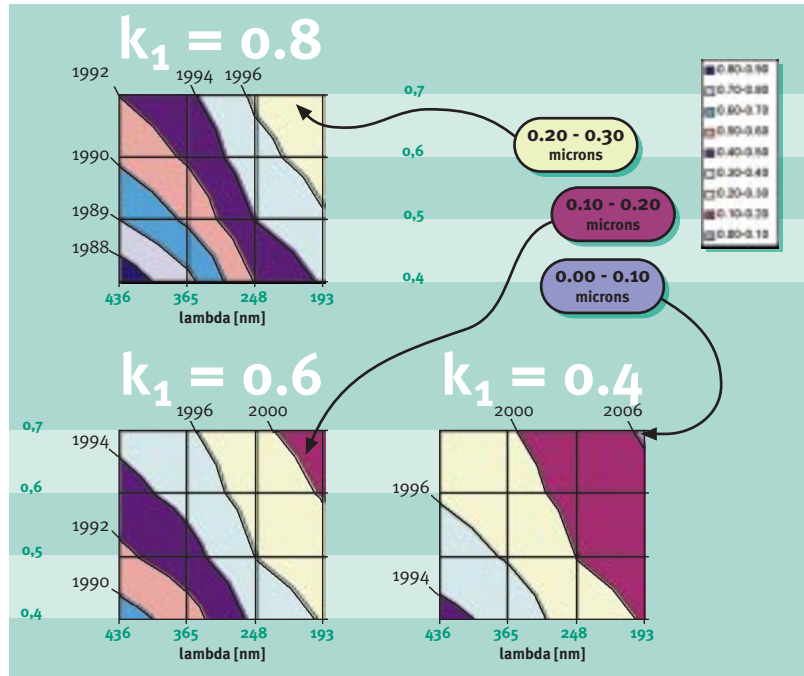


Figure 2.2.4

State-of-the art 5500/500 wafer scanner, capable of high-throughput integrated circuit production on silicon wafers by photolithography with 250 nm resolution. Developed and produced by ASML Veldhoven, The Netherlands.



Meanwhile, the depth-of-focus of this image decreases with the wavelength and the square of the numerical aperture [Hecht, 1998]:

$$\text{depth of focus} = k_2 \times \text{wavelength} / (\text{numerical aperture})^2$$

As with the minimum feature size, k_2 is an imaging constant depending for instance on the coherence of the source and on the resist. A reasonable depth of focus is needed to expose wafers with a certain topography with height variations patterned in previous lithography steps.

Today's photolithographic equipment consists of impressive machinery that is used to repeatedly image a pattern of a mask onto a silicon wafer. There are two basic types of machines. In a wafer stepper, the complete pattern of an integrated circuit (a 'die') is imaged at once. Then the wafer is stepped (moved) and the next die is imaged. In a wafer scanner, each die is imaged line by line by synchronized movements of the mask and wafer (also called 'step and scan'). An example is shown in figure 2.2.4. Such equipment is routinely used in integrated circuit manufacturing to produce structures as small as 250 nm.

The light source used in most present-day industrial processes is a mercury arc lamp of which the ultraviolet line at 365 nm is used. However, this source is in the process of being replaced by a krypton fluoride laser radiating at a wavelength of 248 nm. This improves the resolution and the depth of focus sufficiently to enable imaging of features down to 250 nm. These structures are present in 256 Mb memory chips, which constitute the current generation of circuits to be fabricated. Further gain is possible by utilizing an argon fluoride excimer laser operating at 193 nm as the next deep-ultraviolet (DUV) light source. Additional resolution enhancement techniques based on the use of the phase of the light, such as the use of phase-shifting masks or mask illumination improvements, are increasingly being employed to extend the scope of optical lithography to its limits. Optical lithographers expect that these additional techniques will ultimately enable a resolution of 120 nm using argon fluoride lasers [Wittekoek, 1994]. With the use of a 157-nm wavelength it is expected that features smaller than 100 nm can be printed; researchers from Texas Instruments have produced lines 60 nm wide; and the Japanese research consortium ASET has recently shown that it is possible to fabricate 40-nm lines using optical lithography with 193-nm in combination with a technique called top surface imaging (TSI) [Raaijmakers, 1998]. Still, eventually, optical lithography will have moved into top gear. The inherent physical limitations become more and more evident. For wavelengths below 120 nm, no optical materials are transparent and the development of diffraction-limited lenses is improbable. The question remaining is: which lithographic technique will come next? Several technologies that potentially could be used for nanolithography are described below.

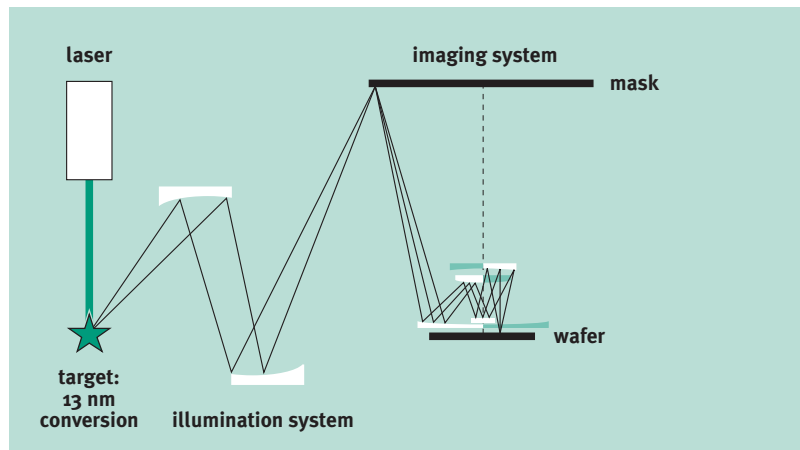
To illustrate some of the technical issues involved, x-ray lithography (XRL) and extreme-ultraviolet lithography (EUVL) are discussed in more detail.

Extreme-ultraviolet lithography

To extend the on-going technological trends to wavelengths in the vacuum-ultraviolet and soft-x-ray range (collectively indicated as XUV) below 100 nm, a few researchers decided to explore processes of a short-wavelength imaging method which includes 'reduction optics' analogous to optical lithography. Such a reduction scheme with the ability of making diffraction-limited images would take full advantage of the short wavelength. The method, initially called soft x-ray projection lithography but later named extreme-ultraviolet lithography (EUVL), uses reflecting optics and masks with special multilayer coatings (figures 2.2.5-9).

Figure 2.2.5

A possible arrangement of a multi-component imaging system using extreme-ultraviolet lithography (EUVL). Curved mirrors with special multilayer coatings are used, first (left) to illuminate a reflecting mask and then (right) to demagnify the mask pattern onto the wafer. Source: ASML.



The preferred wavelength in EUV lithography is 13 nm, just below an absorption edge of silicon. This choice is mainly determined by the use of silicon as one of the components in the multilayer reflective coatings, which basically consist of a stack of coherently reflecting bilayer systems of silicon and molybdenum. The extreme ultraviolet radiation requires optical elements fabricated with a surface accuracy and roughness in the sub-nanometer range. This specification is beyond values achieved so far, yet is being approached rapidly by the optic fabrication experts. The multilayer reflective coating must have equal precision (figures 2.2.6 and 2.2.7) [Voorma, 1992; Schlatmann, 1994].

The optimal light source in EUVL is commonly believed to be a laser-produced plasma source, although compact synchrotron light sources are also an option (see 'x-ray lithography'). A laser plasma is created by focusing the beam of a pulsed, high-energy laser onto a target, usually a metal. The plasma thus produced emits an intense burst of photons in a broad wavelength band from the

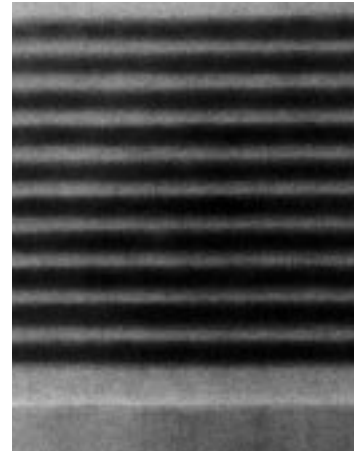
Figure 2.2.6

Facility for the production of multi-layer reflective coatings, based on electron-beam evaporation and in-situ ion-polishing of the layer interfaces. Source: FOM-Institute for Plasma Physics Rijnhuizen.



Figure 2.2.7 (right)

High-resolution transmission electron microscope (HRTEM) image of a molybdenum/silicon multilayer reflective coating with individual layer thicknesses of 3 nm. These mirrors show their best reflectivity at 13 nm where the Si becomes transparent [Louis, 1994]. Source: FOM-Institute for Plasma Physics Rijnhuizen.

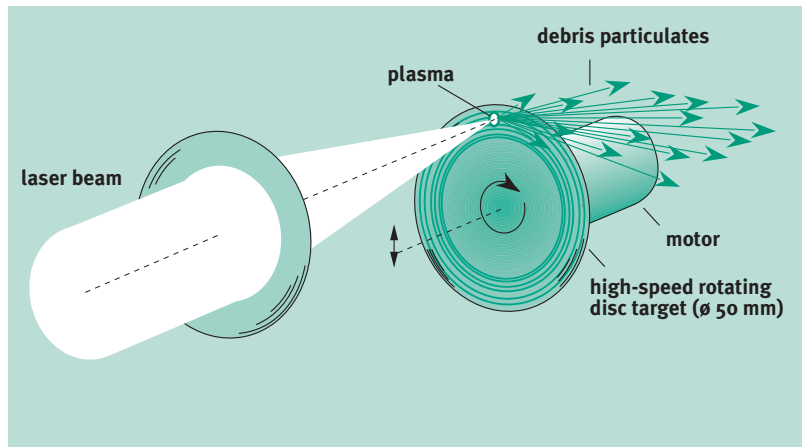


visible to the soft x-ray range, including the desired extreme ultraviolet. The point-like source nature and the high yield make these sources the preferred choice for extreme-ultraviolet lithography. They also allow a continuation of the current ‘granular’ approach (one radiation source per wafer stepper), and thereby enable a relatively evolutionary change in technology.

Extreme-ultraviolet lithography requires high-power laser systems with specification which are quite demanding for present-day lasers [Godard, 1992]. Plasma sources have conceptually been demonstrated with a high average power at 13 nm [Shevelko, 1998], but are still at some distance from the final goal. Before these sources can be used, a method must be developed to mitigate pollution by plasma debris. The target debris created by the focused laser beam can cause substantial contamination of components that face the plasma, such as delicate filters and multilayer-coated condenser optics. A number of solutions have been found to be effective in stopping debris (e.g., figure 2.2.8), all of them leading to suppression of different debris components [Kubiak, 1996, Shmaenok, 1998].

Figure 2.2.8

Example of a method used to suppress debris from a laser plasma source. The laser beam (indicated in white) is focused on the target to create a hot, x-ray emitting plasma. Due to the fast rotation of the target, debris particles, especially the larger fragments, are redirected leaving a debris-free angular zone. Reprinted with permission from [Shmaenok, 1995]. Copyright 1995 SPIE.



Extreme ultraviolet lithography dates from 1981 [Lovas, 1981; Underwood, 1981; Hawryluk, 1989], and has been explored by research groups in the USA, Japan and Europe [e.g., Optical Society of America, 1991-1996]. In several concerted research programs carried out under the auspices of industry, further demonstrations of the concepts of extreme-ultraviolet lithography are now being pursued. Key tasks are the development of a bright extreme-ultraviolet source including a multi-kW laser driver, multilayer coated optics with sub-nanometer figure tolerances, resists and defect-free repairable reflecting masks. In addition, the optics require development of novel at-wavelength test facilities with resolutions ultimately in the sub-nanometer range.

X-ray lithography

An approach proposed early on [Spears, 1972] involves the use of an even shorter wavelengths of about 1 nm, which is in the soft x-ray range. For this wavelength no suitable optics are available, and the imaging scheme reduces to a one-to-one shadow-printing process.

X-ray lithography required the development of an application-specific x-ray source, for which so-called compact synchrotron radiation sources are currently the mainstream approach. These bright sources are basically scaled down versions (figure 2.2.9) of the large synchrotron facilities used for fundamental research. They are being successfully employed in x-ray lithography pilot line plants, for instance at IBM and Mitsubishi.

Figure 2.2.9 (left)

The principle of x-ray lithography (XRL). The radiation is produced by a synchrotron light source and used to expose the wafer through a 1:1 proximity mask. Due to the high absorption in air, most of the components operate in vacuum. See also figure 2.2.10.

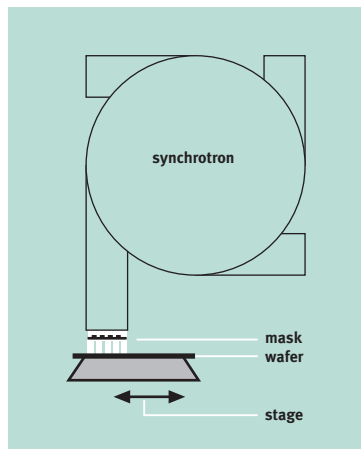
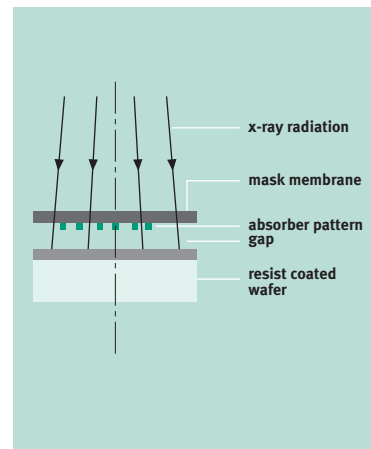


Figure 2.2.10 (right)

Geometry of x-ray lithography.



Although costly (approximately \$25 million), one synchrotron source can have several exposure beam lines and serve up to twenty wafer steppers. The utilization of the cheaper and smaller laser plasma x-ray sources turned out to be limited, due to their point-like source nature and the fact that their emission properties are best at longer wavelengths (the same properties which made laser plasmas the preferred source for extreme-ultraviolet lithography).

The need for an x-ray optical system is circumvented by the basically simple imaging scheme of a one-to-one shadow printing process (figure 2.2.10). A transmission mask is separated from the wafer by a small proximity gap (about 10 μm) to protect the mask against mechanical damage. Structures well below 100 nm have been reproduced faithfully in various laboratories world-wide [e.g., Smith, 1991]. The domain of dimensions down to 70 nm can be covered using traditional (optimized) masks, and 30-nm lines were achieved using phase-shifting techniques [Cerrina, 1997]. X-ray lithography has several other advantages, including the use of a single-layer resist technology and the insensitivity to particle or dust contamination, both explained by the larger penetration power of the x-rays used.

The x-ray proximity print scheme does not take advantage of the short wavelength of the x-rays due to the lack of suitable optics. In contrast to optical lithography, in which a resolution comparable to the wavelength of the light can be obtained, the (Fresnel) diffraction over the finite gap between mask and wafer limits the resolution to about 100 nm, whereas the physical limit for an imaging system would be several nanometers. A resolution of 100 nm is insufficient to produce future chip generations. In principle the practical resolution could be improved by reducing the gap, but the delicate mask requires some minimal distance to protect it from damage for instance due to dust particles. Occasionally, alternative x-ray schemes involving novel types of optics are proposed. For instance, a group at the Massachusetts Institute of Technology (MIT) has devised a scheme involving 'zone plate arrays' to focus parts of the beam through micromechanical shutters onto the surface and claims that it could allow the fabrication of components with a size of 25 nm [Bains, 1996]. It remains to be seen if this claim – and others, for instance on x-ray holographic lithography – can be realized, and subsequently, if the technique is also suitable for commercial mass manufacturing.

In 1998, x-ray lithography still finds support as a route towards nanofabrication of integrated circuits [Geppert, 1998]. However, x-ray mask fabrication is generally considered a non-trivial task that has not been successfully commercialized. Due to the one-to-one reproduction method the mask features should be made to at least the same tolerance as the final circuit structures, while the support membrane cannot be thicker than a few micrometers to ensure sufficient transmission and contrast. Consequently, x-ray masks are delicate and costly, and have kept x-ray lithography from being introduced in production processes so far.

Electron-beam lithography

Due to its flexibility in creating patterns, electron-beam lithography is widely used in research, and is the primary technique for mask fabrication. Although the resolution obtainable is substantially higher than possible with optical production tools today, the throughput of this sequential writing technique is too low for application in mass integrated-circuit manufacturing. Imaging using focusing optics is complicated by space-charge effects, leading to a random blurring of the image above a certain electron throughput. Therefore, the production application of electron-beam writing is nowadays mostly restricted to mask making (for the optical production tools) and small production volume specialties.

The newly proposed SCALPEL technique (scattering with angular limitation projection electron-beam lithography) is an elegant way to circumvent the sequential writing. The ultimate resolution in electron-beam lithography is, contrary to the case of optical lithography, not determined by the wavelength. The wavelength is of the order of 10^{-13} m, which is much smaller than atomic sizes. An electron beam can readily be focused to a spot size of about 1 nm. The resolution-limiting factors in electron-beam lithography strongly depend on the resist properties (section 2.2.6).

To increase the wafer throughput, different electron-beam lithography schemes have been developed (figure 2.2.11) using a round beam (1 pixel), a shaped beam (25 pixels), cell projection (10 thousand pixels) or SCALPEL (25 million pixels). Of these, none have made adequate progress toward becoming a robust manufacturing technique, although SCALPEL is predicted to offer a commercially interesting maximum throughput of thirty 8"-wafers per hour.

The principle of SCALPEL – first proposed in 1984 [Koops, 1984] and developed

Figure 2.2.11

Expected throughput for scanning electron beam lithography with 50 nm features using three different beam shapes. Reprinted with permission from [Broers, 1996]. With kind permission from Kluwer Academic Publishers.

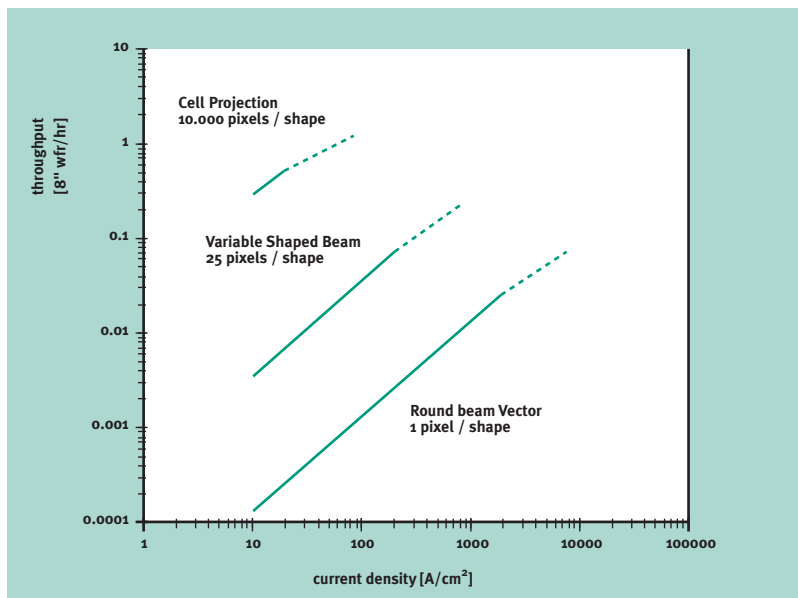
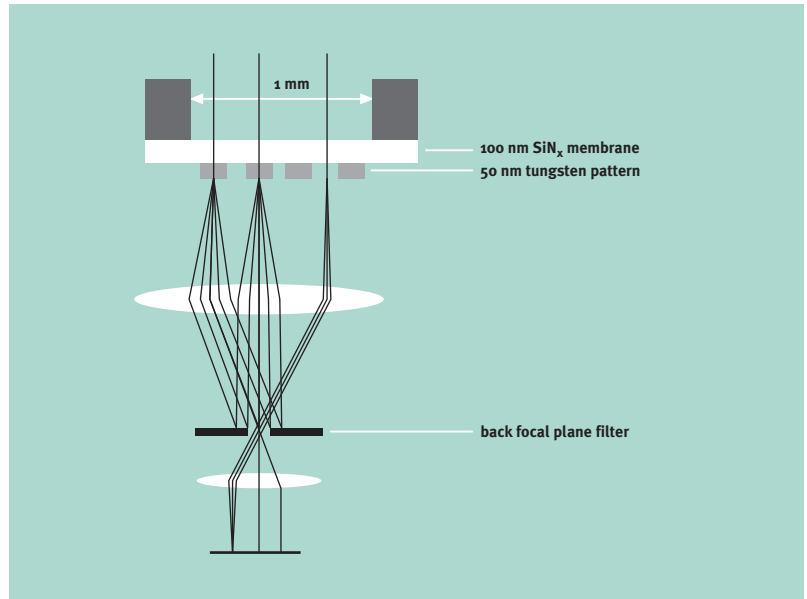


Figure 2.2.12

The principle of SCALPEL (scattering with angular limitation projection electron-beam lithography). The mask is uniformly illuminated by a parallel beam of electrons. Electrons passing through transparent areas (upper right) move virtually straight on, are focused by the magnetic lens and pass through the back-focal-plane aperture to illuminate the wafer. Electrons passing through a scattering area (upper left and middle) form divergent beams that are largely blocked by the aperture. In this way a 4:1 demagnified image of the mask is produced at the wafer plane. Source: ASML.



at Lucent Technologies since 1989 – is schematically drawn in figure 2.2.12. Electrons are not absorbed by the mask but scattered by a tungsten pattern. A filter in the back focal plane absorbs the scattered electrons and hence image contrast is obtained. It seems that SCALPEL has solved the two main obstacles of projection electron-beam lithography. First, SCALPEL uses a scattering mask rather than an absorbing mask (which is susceptible to heating at a limited maximum accelerating voltage), and it does not require the so-called complementary mask for complex structures. Second, the optical scheme allows much higher throughput before space-charge effects destroy the resolution. These two advantages provide the basic means to overcome most of the limitations that prevented the earlier electron-beam attempts from being applied to volume chip production. An additional advantage is that the entire electron beam can be deflected by magnetic fields; optical imaging requires moving parts for this. As a result, it is possible to use a relatively inaccurate stage. The program goal at Bell Laboratories (Lucent Technologies) is to demonstrate the lithographic viability of SCALPEL for circuit production from 180 nm through 50 nm. Patterns of 80-nm wide holes have been reported [Hillenius, 1997]. The ultimate resolution is about 35 nm [Lucent⁷, 1998].

Each image is effectively assembled from many small pieces using a step-and-scan approach. The ‘stitching’ of 0.25 x 0.25 mm² fields has partly been demonstrated. Also, Lucent has found an ingenious trick (‘ghosting’) to correct the proximity effect, although this principle has not yet been implemented in their system. The main risk factors for the development of SCALPEL are that the fabrication of the mask as well as the attainable blur versus throughput have yet to be demonstrated. Finally, SCALPEL is faster than direct-write electron beam

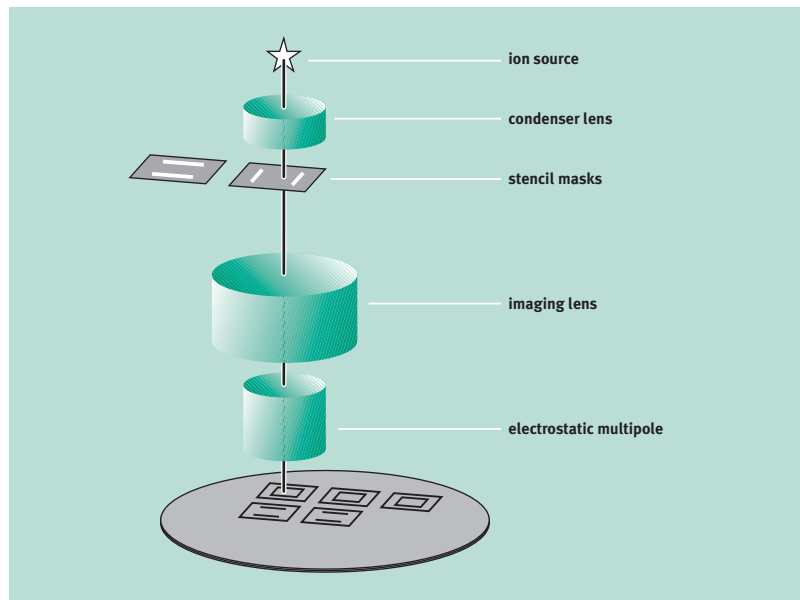
7 Bell Labs Website,
<http://www.bell-labs.com/project/SCALPEL/description.html>,
February (1998)

lithography but will, for fundamental physical reasons, most likely have lower throughput than extreme ultraviolet and ion beam lithography.

Ion-beam projection lithography

The last technique discussed, ion-beam projection lithography (IPL, figure 2.2.13) is typically performed with hydrogen or helium ions. The image construction requires several complementary stencil masks. The machine exposes one image field (die) at a time and steps from die to die. The electrostatic lens system operates at a 4:1 demagnification. Presently, the resolution of the latter lithographic patterning technique is around 180 nm, a resolution which can also be obtained with advanced optical lithography in a much less expensive way. However, ion-beam projection lithography has proven able to print structures well below 100 nm [Bruenger, 1998]. A system that is currently being designed by IMS-Vienna in cooperation with ASML and Leica is expected to demonstrate a resolution below 100 nm by the end of 1999. Also, according to a Sematech Cost of Ownership analysis, ion-beam projection lithography is cheapest of all alternatives. The main risk factors for the development of the technique are the mask fabrication, the design of the ion imaging system, the demonstration of a good blur versus throughput and of the stitching of complementary masks.

Figure 2.2.13
Principle of ion-beam projection lithography. Source: ASML



Other techniques

The techniques discussed before are the most important alternatives for nanolithography. However, there are other techniques for nanostructuring of surfaces that may have particular advantages as a tool for nanoscale science and technology. For instance, direct beam-enhanced techniques do not employ

resist for pattern definition. Examples are direct sputtering of a substrate material by a focused ion beam, direct deposition of metal or silicon atoms from a focused ion beam (single atom lithography [Ahmed, 1996a]), and direct deposition from a precursor gas under a focused electron beam. Careful evaluation of practical parameters suggests that typical best resolution that may be expected is also around 5 nm [de Jager, 1997]. A factor inhibiting further precision using focused ion-beam lithography at room temperature is surface migration of ions, which causes the formation of nanoparticles consisting of typically 10 to 100 atoms. In the following sections, several additional recently developed techniques are discussed.

Conclusion

Fabrication of the newest generations of integrated circuit devices continuously imposes higher demands on lithography, the main pattern definition technique. Optical lithography is expected to be applicable down to 120-nm patterns using ultraviolet radiation of 193 nm. Beyond that limit, several options for new production technologies exist including the use of ions, electrons, and short-wavelength photons. Development of nanolithography technology and corresponding tools is needed for the most promising techniques discussed above to determine the 'show stoppers' and to reduce the risks. Mask technology is a key element for all projection methods.

The interested reader can find more detailed information in, for instance, [Rai-Choudhury, 1997].

2.2.2 MICROCONTACT PRINTING

*N. Willard*⁸

Introduction

Based on a centuries-old stamping technique, microcontact printing is a simple method capable of producing (sub)micron or nanometer details in nanometer-thick monolayers. These monolayers are self-assembled and self-ordering layers only one molecule thick.

Microcontact printing was pioneered by Whitesides' group at Harvard University [Kumar, 1992] and is now studied and used by several other groups [Larsen, 1997]. These patterned, self-assembled monolayers (SAMs) are being used because they offer chemically selective processes at surfaces and interfaces. Furthermore, microcontact printing is a relatively fast printing method compared to the time-consuming patterning of an electron-beam exposure [Biebuyck, 1997a].

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Principle

The formation of a stable, well ordered, self-assembled monolayer is the key process of microcontact printing. One of the best studied examples of self-assembled monolayers is the formation of a thiol monolayer on gold (a thiol is a reactive sulfur group that anchors the molecule chemically to the surface, see figure 2.2.14 (f)). Other examples are thiols on silver and copper [e.g., Larsen, 1997], silanes on silicon oxide [Jeon, 1997] and carboxylic acids on oxides [Tao, 1993]. Several other combinations are claimed in patents [Kumar, 1993]. Not all of these monolayers can be used for microcontact printing. Stable monolayers are only formed when reagent, substrate and reaction conditions are carefully selected. Important factors are: a clean substrate without interfering contamination, a strong interaction between the substrate and reagent and a long carbon chain in the reagent to obtain a well-ordered layer. Only these self-assembled monolayers are stable enough to withstand the sometimes aggressive conditions in the further processing of the monolayer pattern.

Microcontact printing uses a flexible rubber stamp to apply small quantities of a specially selected reagent solution as 'ink' onto the surface (figure 2.2.14). The stamp is a flexible silicon rubber that is hardened in contact with a master.

Figure 2.2.14

Process for the production of a microcontact stamp and the formation of self-assembled monolayers on a substrate.

a A master is made from a resist pattern (white) on a silicon wafer (dark grey) using optical or electron-beam lithography.

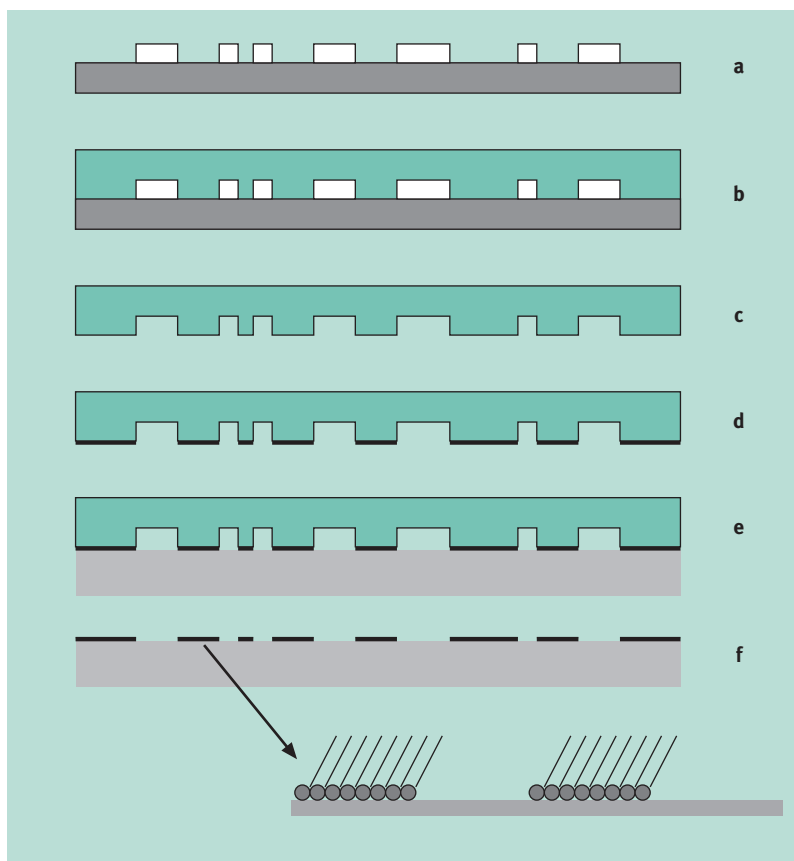
b Silicon rubber (green) is molded on the master.

c A silicon stamp (green) after peeling from the master.

d Stamp after inking with the reagent solution (black).

e Inked stamp in contact with substrate (light grey).

f Surface with self-assembled monolayer; enlarged the expected simplified molecular conformation of a self-assembled monolayer (black) with a long hydrocarbon tail.



For a stamp with (sub)micron details, a silicon wafer with a resist pattern created with photolithography is used as a master. A master with nanometer details can be made with electron-beam lithography. Obviously, special care and clean room procedures must be used to prepare the master and stamp. Every error, particle, or scratch will be reproduced in the monolayer pattern. Due to their high flexibility, silicon stamps will adhere spontaneously to the surface.

The height and width of the pattern on the stamp is crucial for a reproducible printing process. If the protruding structures (typically lamellae – thin plates of material) are too high and narrow or too close, they will collapse under the weight of the stamp or will adhere to each other [Delamarche, 1996]. Lamellae that are either too low or spaced too far apart result in extra (unwanted) contacts of the stamp with the surface, and hence in a non-reproducible pattern. The height of the lamellae varies between 0.6 and 4 μm , depending on the pattern.

After ‘inking’ with a reagent solution, the stamp is brought in contact with the surface. Inking is fairly simple, the stamp is wetted by a cotton tip drenched in the reagent solution and blown dry. This results in a thin film covering the whole surface of the stamp. Since only the top of the lamellae will contact the substrate, these are the only regions where the reagent can react with the substrate. The thiol groups at these positions react so fast when they touch the (gold) surface that further reactions and further flow of reagent is prevented. In this way, an exact replica of the stamp is formed. The monolayer pattern has a height of 2 nm and lateral details of 20 nm up to 150 μm , depending on the stamp. Due to the flexibility of the stamp, curved or rough surfaces can also be printed.

The different properties of printed and non-printed regions are exploited in further processing using, for instance, selective etching or deposition, depending on the quality of the monolayers. Another option is to fill the free surface between the printed monolayer with a reagent with different functional end groups and hence different interfacial properties. Several reagents with a broad range of different functional end groups, such as a hydroxyl-, an amino-, or a carboxylic acid group, are either commercially available or described in literature [e.g., Jeon, 1997].

Problems

Because microcontact printing is a replica process, another sophisticated method will be necessary to produce the master. The pattern reproduction can be distorted by particles and by the low rigidity and easy deformation of the silicon stamp [Biebuyck, 1997b]. In practice, the stamp can easily be used 25 times. The limits to re-use have not yet been investigated well although they are obviously important for applications. Furthermore, an absolutely clean substrate is mandatory for the formation of high-quality monolayers. High-quality

monolayers are only possible for a few selected combinations of materials and reagents, although the number of combinations is still increasing. A last point of concern is that monolayers are fairly robust but they are only one molecule thick. The stability and resistance of these layers is not always satisfactory for certain processes.

Applications

As we have already mentioned, several promising applications for microcontact printing exist. First of all, microcontact printing is a feasible option for reproducing (sub)micron patterns over a large area, for reproducing (sub)micron patterns that would require long exposure times using optical lithography and also for nanolithography [Xia, 1996], for instance for the fabrication of quantum dots (section 2.3). The method can produce smaller details than other printing techniques. One good example of work in this field stems from Michel's group at IBM [Biebuyck, 1997a]. Lines in an electron-beam resist with 50-nm spacing were reproduced by microcontact printing in a thiol monolayer on gold and imaged with electron microscopy. The ultimate resolution of microcontact printing is probably about 20 nm. This resolution is much better than photolithography and comparable to electron-beam lithography. It implies that features only 100 thiol molecules across are present in the pattern; better resolution using these molecules can only be achieved by bottom-up techniques.

Multilayering, the application of several patterns onto each other, has also been demonstrated. This is of vital importance because integrated circuits consist of vertically interconnected metal tracks lying on different layers. Since microcontact printing imposes special demands on the pattern – in particular, empty areas present a problem – and the monolayer cannot withstand all the aggressive chemical treatments that normal photoresists can, microcontact printing will never completely replace photolithography. It may, however, become a valuable tool in reproducing suitable nanoscale patterns fabricated with other serial high-resolution patterning techniques.

One of the strongest points of microcontact printing is its control over interfacial interactions, namely the adhesion and chemical reactivity between 'ink' and substrate. No other printing technique has the potential for all of the following applications: selective etching, selective adsorption, selective adhesion, the activation of chemical reactions (catalysis), the production of selective (bio)sensors, controlled wettability⁹, and the control over a patternwise growth of cells. One fine example of this control over interfacial interactions is the 'mass' fabrication of microlenses [Kumar, 1995] and channel waveguides [Kim, 1996]. These microlenses are formed as a result of poor wettability: the ink forms spherical droplets to minimize the contact area with the surface. Another possible application of controlled wettability is the measurement of air humidity. More applications of this control of interfacial reactivity by microcontact printing are easily

⁹ the extent to which a surface is wetted by a liquid

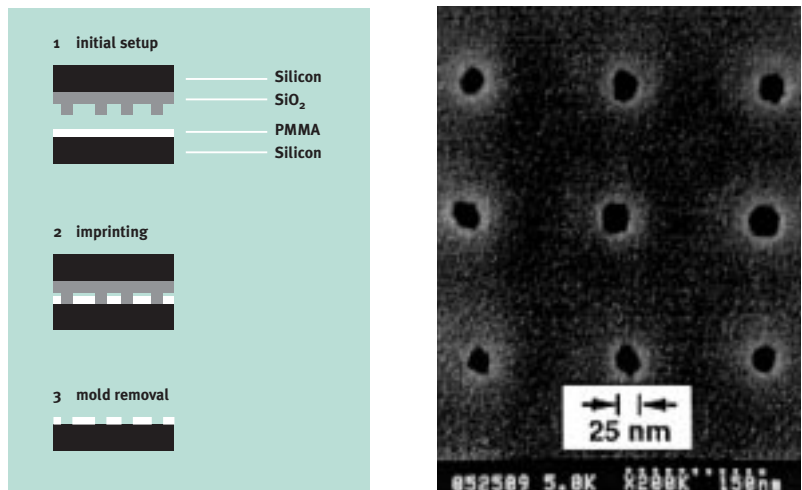
envisaged, such as defining patterned particle layers (for the production of phosphor layers in TV screens) or defining chemically deposited (electroless) metal film patterns on glass, as with silver-plated Christmas-tree balls.

The imprint technique

A related but essentially different technique for pattern transfer is imprinting. The essence of the imprint technique is that a reusable mold is pressed hard into a thin thermoplastic polymer film on a substrate, so that polymeric material is removed from the imprinted regions. The resulting pattern serves as a lift-off mask. Figure 2.2.15 shows a schematic of this parallel processing technique as well as a resulting dot pattern [Chou, 1996]. The first experiments indicate that the achievable critical dimensions depend only on the mold dimensions that can be prepared with one of the above-mentioned serial writing techniques. A combination of imprinting and scanning probe lithography (section 2.2.4) or high-voltage electron beam lithography (section 2.2.6) may become important for the fabrication of molds for nanoelectronic devices.

Figure 2.2.15

Illustration of the imprint technique. In (a) the schematic of the process is shown. (b) An electron micrograph of a dot pattern imprinted into a thin thermoplastic polymer (PMMA) layer. The dots have a 25-nm diameter and a 120-nm period. Reprinted with permission from [Chou, 1996]. Copyright 1996 American Association for the Advancement of Science.



Conclusions

Microcontact printing can produce patterns with (sub)micron and nanometer features in nanometer-thin films in a relatively simple and reliable manner. For applications involving large areas or requiring long exposure times when using lithography, microcontact printing could possibly replace lithography. Microcontact printing can accurately control the interfacial properties, leading to several promising applications. A related technique, imprinting, is also promising.

2.2.3 ATOM LITHOGRAPHY

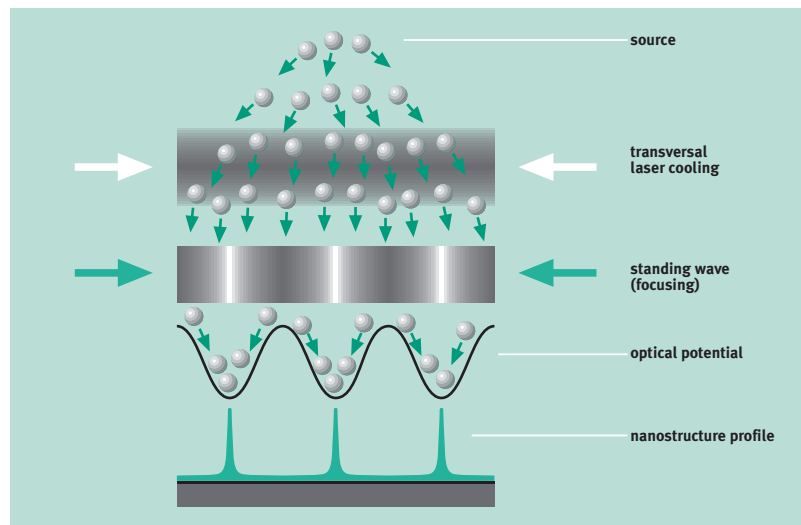
E. Jurdik, H. van Kempen¹⁰

Introduction

The previous sections discussed various alternatives to optical lithography. Recently, atom lithography emerged as a promising method of massively parallel patterning with nanometer-scale resolution. In this case, a beam of atoms is projected onto a surface through a laser interference pattern. The diffraction limit of this approach is lower than that of optical lithography due to the short de Broglie wavelength (Planck's constant over the atomic momentum) of thermal atoms. By using atoms that stick well on surfaces, atom lithography can be applied to write structures directly onto substrates. On the other hand, metastable rare gases or chemically aggressive atoms can be used to pattern surfaces in an indirect way: the pattern is first imaged on a special resist and then transferred to the substrate using other methods, such as selective etching. The principles of atom lithography are schematically presented in figure 2.2.16.

Figure 2.2.16

Illustration of the basic principles of atom lithography. A laser-cooled atomic beam is deposited onto a substrate through a standing-wave laser mask to form a nanometer-scale structure. Neutral atoms emerge from a vapor source exhibiting a thermal spread of transversal velocities that is reduced by the optical cooling of atoms. The atoms then enter standing wave laser light and are focused onto a substrate to form a periodic nanometer-scale structure.



Atom lithography relies on fundamental interaction processes between atoms and photons. An atom moving in a near-resonant laser field exhibits in general two types of forces: the spontaneous force and the dipole force. The former is a result of absorption-spontaneous emission radiative cycles while the latter is due to absorption-stimulated emission cycles. The dipole force on a neutral atom in a laser standing wave can be derived from an optical potential which, to the first approximation, is linear in the light intensity. Atoms moving through such an optical potential tend to oscillate around its minima. The focusing of atoms can be qualitatively understood from the analogy with the focusing properties of a lens with a parabolic refractive index profile in conventional optics.

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Thus, near-resonant standing-wave light forms an array of atomic lenses. Neutral atoms can be focused, depending on the sign of the detuning of the laser frequency from the atomic transition, where positive detuning results in focusing to the nodes and negative detuning to the anti-nodes. The period of the resulting structure is consequently equal to half of the light wavelength. Because the dipole potential is weak compared to typical transversal thermal kinetic energies of atoms, the atomic beam needs to be collimated before focusing. The requirements for atom lithography can not be met by mechanical collimation, since it would result in an extremely high loss of flux. Therefore, optical collimation methods based on the dissipative light forces on atoms are used. In the simplest case, atoms moving across two counter-propagating, red-shifted, weak laser beams are cooled due to the spontaneous force and the Doppler effect. The limit of this Doppler cooling scheme results in an atomic beam with transversal kinetic energies corresponding to an effective temperature of the order of a few hundred microKelvin (μK). Other cooling mechanisms have been identified and successfully applied to prepare atomic beams with sub-Doppler temperatures [Cohen-Tannoudji, 1990]. Chromium atoms with transversal temperatures as low as $23 \mu\text{K}$ have been reported [Scholten, 1997]. This implies a divergence of approximately 0.009° for a chromium beam exiting an oven at 1800 K .

Resolution

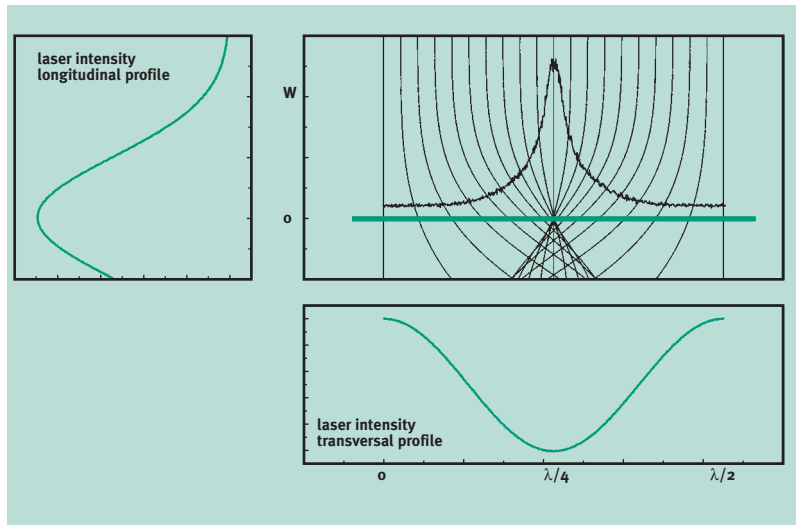
The resolution and contrast (quality) of structures grown by atom lithography are limited. First, the diffraction of atomic de Broglie waves ultimately restricts the resolution to about a few nanometers. Further restrictions, imposed by the atomic and laser beam parameters, have been investigated with semi-classical simulations (figure 2.2.17). The atoms emerging from an atomic source have different velocities and thus different interaction times with the laser standing wave. This gives rise to an effect known as chromatic aberration of an atomic lens. For the case of thermal atoms, though, chromatic aberration appears to have only a weak influence on the achievable quality in comparison to the other effects involved. The atomic beam divergence, which is due to the low temperature limit of the laser cooling schemes, has been found to have a very pronounced influence on the quality of the structures. At the same time, the beam may contain atoms that are not affected by the laser radiation, such as those relaxing to a metastable state in the laser cooling beam or those belonging to another isotope. These conditions, though, are element specific.

Turning now to the laser parameters, the detuning of the laser frequency from the atomic resonance, the laser power and the laser beam waist each individually affect the form of the optical potential and thus the focusing properties of an atomic lens. In principle, the larger the detuning the more harmonic-like the potential and the better the resolution that can be achieved. However, the laser

power required to bring the atoms into a focus in a laser beam increases with increasing detuning. So, in practice a compromise has to be reached. The role of the laser beam waist can be qualitatively illustrated by the role of the focal length of a lens in optics: the smaller the focal length the better the focusing. Limitations on the resolution of atom lithography also arise from the effect of surface diffusion of atoms. This can be quite substantial and, therefore, requires a thorough study to be performed. Finally, the influence of the quantum nature of atom-photon interaction should be investigated. Figure 2.2.17 shows our simulation of the growth of a chromium structure under standard experimental conditions resulting in an achievable resolution of 20 nm and a contrast 10:1.

Figure 2.2.17

A semiclassical computer simulation of chromium atom lithography. The resulting nanostructure profile is calculated by tracing trajectories of 250,000 atoms exiting an oven at 1800 K and cooled in the transverse direction to 20 μ K. After choosing the laser detuning¹¹, the laser power (3 mW) is optimized for focusing. The laser beam is assumed to have a Gaussian profile with a waist of 100 μ m. The final resolution and contrast are 20 nm and 10:1, respectively. Calculation by E. Jurdik.



At this point a short comment on the (amazing) atom laser is appropriate. An atom laser produces a beam of coherent atoms, just as a laser produces coherent light. In the opinion of the authors, an atom laser could solve the beam collimation problem. Although some results in the field have been reached and the progress is very rapid, the practical development of an atom laser and its usefulness for nanotechnology are still a matter of pure speculation. One problem is that no one has, as yet, presented a scheme that could produce sufficient beam intensity for nanotechnology applications.

State of the art and possible applications

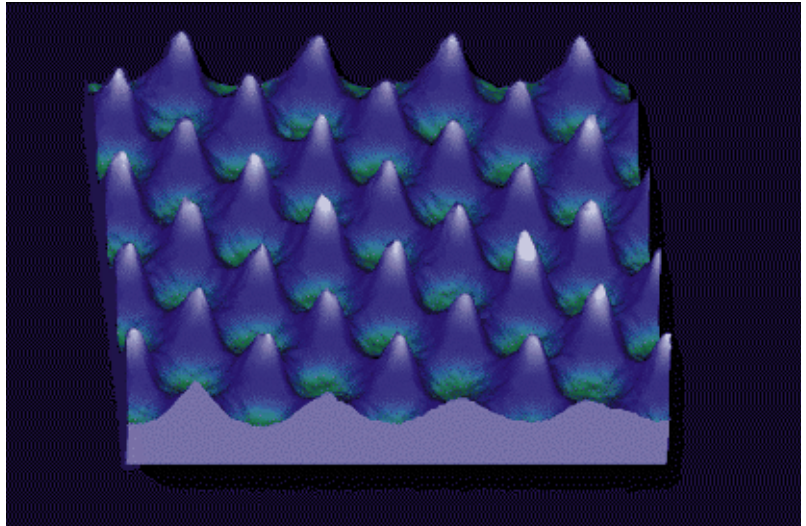
As a part of the broad field of atom optics, atom lithography has attracted a lot of attention in a number of laboratories worldwide. Different atomic species have been used to create various structures. In the first direct evidence of atom lithography, a sodium beam was focused to create a one-dimensional grating-like structure [Timp, 1992]. Subsequently, chromium atoms have been used to

11 200 MHz from the chromium resonance at a wavelength of 425.55 nm

produce nanometer-thick lines [McClelland, 1993], a square lattice of equidistantly spaced features [Gupta, 1995] (see figure 2.2.18), and a two-dimensional structure with a hexagonal symmetry [Drozdofsky, 1997]. Also, aluminum [McGowan, 1995] and cesium [Lison, 1997] atoms have been deposited resulting in one-dimensional periodic nanostructures.

Figure 2.2.18

An atomic force microscope image¹² of a two-dimensional chromium nanostructure grown with atom lithography. The features are separated by 213 nm, having a height of 13 nm and a width (at half the maximum height) of 80 nm. Reprinted with permission from [Gupta, 1995]. Copyright 1995 American Institute of Physics and American Vacuum Society.



The number of elements that can be directly manipulated with just one laser frequency is restricted. However, the created structures can not only be used directly but may serve as a mask or a seed layer for other materials. Using atom lithography, a certain amount of unintended background will always be present. For applications requiring separated nanostructures this can, in principle, be removed by some post-deposition processing. Background removal by use of a reactive-ion etch plasma has been demonstrated on chromium, giving rise to an array of parallel chromium wires as narrow as 68 nm [McClelland, 1998]. In the same experiments the transfer of the pattern to a silicon substrate was reported. With the subsequent chromium removal by a wet etch this could have resulted in a silicon nanostructure. The same procedure can be used to pattern other substrates, such as the technologically important gallium arsenide. The periodic structures created by atom lithography show extremely high precision through relatively large areas, making this tool attractive for metrology and calibration standards. More complicated periodic patterns than lines and dots may be written by moving the substrate with a nanometer-scale accuracy or by using more complex optical fields. Finally, the application of atom lithography to produce magnetic nanostructures of materials like iron and manganese could have an impact on the technology of magnetic recording. A data storage density of 240 Gbit/in² seems achievable. In principle, the integration of layers to fabricate a three-dimensional structure would also be possible [Rahe, 1997]. The inherent

¹² http://physics.nist.gov/Divisions/Div841/Gp3/epg_files/atom_dots_proj.html

massive parallelism and ultra-high-vacuum (UHV) compatibility of atom lithography make it very attractive for further *in vacuo* scientific processing, such as the investigation of magnetic and optical properties of these periodic mesoscopic structures.

2.2.4 SCANNING PROBE NANOFABRICATION

Ch. Van Haesendonck¹³ and L.J. Geerligs¹⁴

Introduction

Recently, it has become clear that a scanning probe microscope (SPM), where a sharp probe moves within a distance of the order of 1 nm from a surface, not only allows to image this surface down to the atomic level (chapter 5), but also allows to modify it in a controlled way down to the nanometer level [Rohrer, 1995; Brandt, 1997]. Many techniques for scanning probe lithography have been presented in literature [Marrian, 1993]. On conducting surfaces, the scanning tunneling microscope (STM) tip can serve as a low-voltage electron source for the exposure of thin electron-sensitive resist layers (scanning probe lithography). This method allows writing with very-low-energy electrons in very thin resist layers, thereby avoiding most of the resolution-limiting aspects of conventional electron-beam lithography. Alternatively, by giving short voltage pulses, one can deposit small amounts of the tip material on the substrate via field evaporation or, after passivation with hydrogen atoms, one can locally depassivate a surface such as silicon. As shown in figure 2.2.19, under the appropriate experimental conditions – usually ultra-high vacuum (UHV) and low temperature – it becomes even possible to manipulate individual atoms on a conducting surface. In contrast to the scanning tunneling microscope, the atomic force microscope (AFM) can be used to pattern and investigate both conducting and non-conducting surfaces under ambient conditions, but usually not with atomic resolution. The very controlled mechanical contact between the sharp tip and the surface allows to etch small grooves in a soft layer or to even induce atomic-scale modifications [Mamin, 1992; van Loenen, 1989].

The high-resolution lithographic techniques discussed elsewhere in this chapter do not provide the ultimate resolution that scanning probes can offer, but are competitive down to about 5 to 10 nm. As a rough guide-line, scanning probe fabrication is a valuable option (a) where and when resolution below about 20 nm is required, and (b) when advanced process control is required, such as cleanliness or a combination of lithography and atomic-level surface verification. The technique is probably essential when resolution at the molecular scale is required.

The field is under strong development. The following gives an overview of most of the promising or even ‘proven’ techniques, together with their advantages (the achievement of atomic resolution) and drawbacks (mainly the low writing

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speed). The working principle of scanning probes and their use as nanoscale-resolution microscopes are explained in detail in chapter 5.

Surface modification with the scanning tunneling microscope

Basically, the environment of a scanning probe consists of a sample with a flat surface, a very sharp probe which is scanned across the surface by piezo-electrical ceramic, a distance-dependent tip-sample interaction, a feedback mechanism to control the tip-sample distance, and a computer for controlling the tip and for data acquisition. By scanning the surface while keeping the tunneling current constant, one can obtain a topographic image of the surface with atomic resolution (below 0.1 nm).

The scanning tunneling microscope is based on the quantum-mechanical tunneling of electrons between a conducting tip and a conducting surface when they are brought very close to each other while applying a voltage difference. The same principles which allow the scanning tunneling microscope to image the atomic structure of materials, are now also being used for lithographic patterning with nanometer resolution. During the last few years, several new lithographic procedures have been proposed to obtain nanosized features. Some of these procedures have even allowed to prepare working submicrometer transistors. As discussed in section 2.6, classical device concepts based on the field effect may fail at the nanometer scale. Consequently, totally new device concepts based on quantum mechanics have to be introduced for the development of future nanoelectronics.

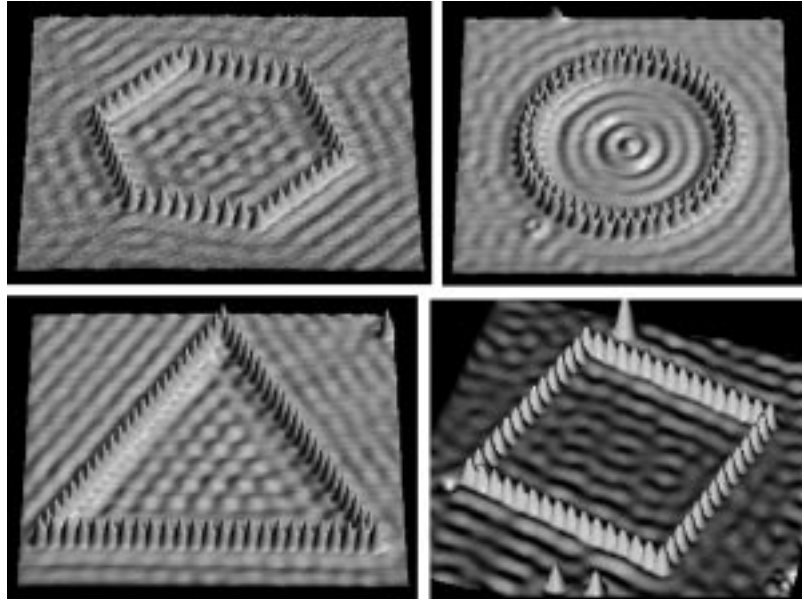
Manipulation of individual atoms and molecules

Individual atoms on a surface can be manipulated with the scanning tunneling microscope by relying on the strong interaction between tip and surface at small working distances [Eigler, 1990]. By sliding atoms to exactly controlled positions a structure can be built atom by atom, and one can even construct artificial molecules out of their constituent atoms (see also section 2.5). Figure 2.2.19 shows an example of iron atoms that were positioned on a copper surface to form various shapes. More examples¹⁵ can be found on the IBM website; see also figure 5.2.4. Atom sliding has been a very early and so far the most spectacular demonstration of scanning probe lithography. It has resulted in, for example, model systems for two-dimensional artificial atoms (section 2.5) and magnetic impurities in superconductors. Apart from individual atoms, molecules can also be manipulated [Gimzewski, 1994]. The manipulation of atoms and molecules is related to a nanofabrication technique that is often called mechanosynthesis. In principle, it therefore forms one possible road towards molecular nanotechnology as proposed by Drexler [Drexler, 1992]. In particular, scanning probes are proposed to fabricate the first artificial molecular assembler, a molecular machine that can manufacture molecules (sections 1.1, 4.10 and 4.11).

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¹⁵ <http://www.almaden.ibm.com/vis/stm/>

Figure 2.2.19

Copper surface modified by the addition of some iron atoms using a scanning tunneling probe. The images show how the electron clouds of the copper surface electrons have been modified by the addition of the iron atoms. The interference patterns are a manifestation of the quantum-mechanical wave nature of electrons. Courtesy of Don Eigler, IBM Almaden, USA.



Unfortunately, in order to reach these ultimate limits of miniaturization, usually severe restrictions have to be imposed with respect to the environmental conditions. In order to avoid contamination on an atomic scale, it is necessary to work in ultra-high vacuum.

Moreover, in order to sufficiently slow down the mobility of the surface atoms, liquid helium-cooling to 4.2 K is necessary to achieve the working temperatures required for atom sliding. The environmental conditions presently limit the industrial applications of atomic and molecular manipulation with scanning tunneling microscopes, and complicate for instance the attempt by the US company Zyvex¹⁶ to fabricate the first molecular assembler. On the other hand, recent reports have indicated that it is possible to manipulate atoms that are loosely ‘sticking’ to the surface of a silicon wafer even at room temperature or elevated temperature [Abeln, 1995].

Atomic resists

Alternatively, the scanning tunneling microscope – or a metallized atomic force microscope – may be used to perform electron lithography with the low-energy electrons (1 to 10 eV) produced by the tip. An important example of this technique employs a hydrogen passivation layer saturating the dangling bonds on a silicon surface [Lyding, 1994]. An artist’s impression of this process is shown in figure 2.2.20.

¹⁶ <http://www.zyvex.com>

Figure 2.2.20

Artist's impression of scanning probe lithography with an atomic resist. For a color print see page 94.

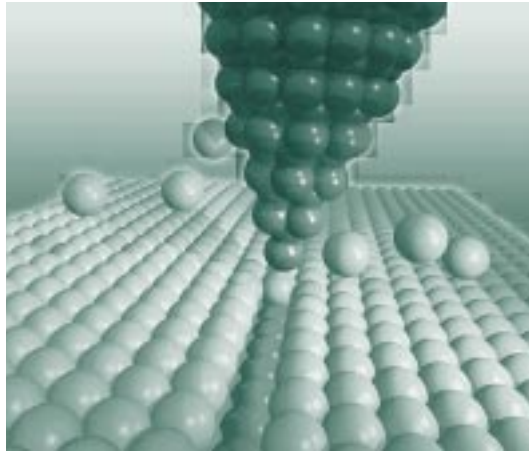


Figure 2.2.21

Scanning tunneling microscope image illustrating the removal of a passivating layer of bonded hydrogen atoms from a silicon surface with the scanning tunneling microscope in ultra high vacuum. The approximately 2-nm-wide lines forming the letters correspond to the de-passivated areas. The total picture size is 40 nm x 40 nm. Reprinted with permission from [Lyding, 1994]. Copyright 1994 American Institute of Physics and American Vacuum Society.



Figure 2.2.22

The DIMES¹⁷ logo written on a silicon surface with a scanning tunneling microscope. The vertical lines are rows of dimers (double silicon atoms) with a spacing of 0.7 nm; the characters are about 9 nm large. Reprinted with permission from [Geerligns, 1997]. Copyright 1997 Kluwer BedrijfsInformatie.



¹⁷ DIMES = Delft Institute for Micro-Electronics and Submicron technology

Patterns can be created by removing the hydrogen under the influence of the high field or current from the scanning tunneling microscope tip. It has been demonstrated that in ultra-high vacuum, where the best resolution is obtained, hydrogen atoms can be removed one at a time [Hashizume, 1996]. Pattern transfer has been atomically accurate in the case of gallium: a metallic wire was effectively created atom by atom. The removal of a passivating layer of hydrogen is shown in figure 2.2.21. Another example is shown in figure 2.2.22. Applications of such a resist rely on the strongly modified physical and chemical properties of the de-passivated areas.

Electron beam lithography with the STM

Electron beam lithography with the STM is very similar to classical electron-beam lithography which is done with the high-energy electrons (10 to 100 keV) produced in an electron microscope. The important advantage of using much lower acceleration voltages is that the effect of the backscattering of electrons by the substrate ('blooming') is strongly reduced, resulting in a smaller exposed area and hence also in a reduced minimum line width. An inconvenience of the low electron energy is that the electron-sensitive layer has to be very thin (1 to 10 nm, depending on the voltage) in order to overcome the small penetration depth of the low-energy electrons into the resist layer and to conserve the limited tip-to-sample distance which is imposed by the tunneling process.

Several types of resist material have already been proposed for exposure with the scanning tunneling microscope. Thin evaporated metal halide films such as calcium fluoride dissociate under an electron bombardment. The fluorine is released as a gas, while the calcium remains on the surface. The non-dissociated calcium fluoride in the unexposed areas can be washed away and the metal pattern can be transferred in the underlying substrate using dry etching [McCord, 1986]. Line widths down to 20 nm were obtained in this way.

Disadvantages of the technique are the low sensitivity and bad reproducibility. Unfortunately, the use of spin-coated layers of PMMA resist to overcome these problems resulted in a rather limited resolution of only 100 nm [McCord, 1987]. The Langmuir-Blodgett (LB) technique may provide an alternative to create a suitable resist layer. It can be used for controlled deposition of a few self-assembling monolayers of electron-sensitive organic molecules (mainly so-called fatty acids). Different molecular structures have been investigated, including PMMA [Zhang, 1989]. After dry etching, line widths down to 15 nm can be obtained in the underlying substrate, but the technique lacks a good reproducibility and it is hard to obtain high-quality, continuous lines over large distances. These difficulties mainly arise from the inhomogeneity and instability of the Langmuir-Blodgett film, which are very dependent on the substrate and on the deposition conditions [Vithana, 1995]. In an alternative approach, which relies on changes in the conductance of the Langmuir-Blodgett film after expo-

sure, the film can be directly used for information storage with bits having a size of 10 nm [Yano, 1996].

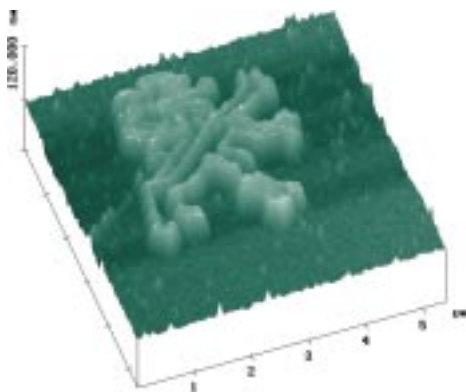
An electron-sensitive monolayer formed by molecular self-assembly has been used to fabricate lines of different metals and having a width down to 15 nm via local exposure with the scanning tunneling microscope [Marrian, 1990]. In this case, precursor molecules from a solution or the vapor phase react at the interface with the substrate to form layers of monomolecular thickness and become chemically bonded to the surface. Again, it proved very difficult to prepare long, continuous lines and the reproducibility of the technique is poor. Due to the relatively high voltages at which the exposure takes place, it is difficult to work under ambient conditions, where electrical discharges can locally destroy the monomolecular resist layer. Therefore, and in order to maintain the mechanical stability of the resist layer during processing, it is often necessary to work in a controlled atmosphere such as nitrogen.

Local oxidation

The scanning tunneling microscope has been used successfully for the local oxidation of a silicon surface in air [Dagata, 1991]. The surface of a doped silicon wafer has to be passivated first in a hydrogen fluoride (HF) solution, which removes the natural silicon oxide (silica) layer and replaces it with a hydrogen passivation layer that is able to prevent further oxidation in air for several hours. When under ambient conditions a voltage exceeding a certain threshold value is then applied between the surface and the tip, the hydrogen passivation will be locally replaced with an oxide layer. This relatively thin oxide layer can then serve as an effective mask for selective etching to transfer the written oxide pattern into the underlying silicon substrate [Snow, 1995]. Figure 2.2.23 gives two examples of structures which have been obtained via the local oxidation technique.

Figure 2.2.23

Patterns written on a silicon wafer with the local oxidation technique. The lighter areas correspond to the oxidized parts of the silicon. The darker areas were not oxidized and could therefore be selectively etched. Left the 'Flemish lion' [Vullers, 1998]. Incidentally, the right upper picture clearly shows the effect of a double tip, which illustrates that a sharp tip is essential for obtaining high-quality structures if the process requires a relatively high voltage. Right figure reprinted with permission from [Kramer, 1995]. Copyright 1995 Elsevier Science.



Recently, it has been shown that thin titanium films and aluminum films can also be oxidized at the nanometer scale with a scanning tunneling microscope [Matsumoto, 1996; Snow, 1996]. The writing speed and resolution for the local oxidation technique are comparable to the results which have been obtained for the local exposure of a resist layer, but the oxidation technique has the important advantage that it works reliably and gives reproducible results, provided the degree of humidity can be kept constant [Kramer, 1995]. Local oxidation of materials combined with subsequent pattern transfer has been one of the most successful techniques so far for device fabrication (see below).

Other techniques

Transport of atoms between tip and surface can occur via field evaporation if the electric field is sufficiently large (about 10 V/nm). Depending on the polarity of the electric field, this leads to evaporation and desorption of material from the tip or the surface, and either mounds or pits can be created on the surface. The best resolution under ambient conditions obtained so far are features having a width of 10 nm and a height of 2 nm, for a golden tip on a gold surface by applying a voltage pulse to the tip [Mamin, 1990]. The local field evaporation works in ultra-high vacuum as well as in air for materials such as gold which have a sufficiently low threshold for field evaporation. Nevertheless, satisfactory results have also been reported for a tungsten tip or a p-type silicon surface [Shedd, 1990]. Because the working conditions for local field evaporation and desorption are clearly less stringent than for the atomic and molecular manipulations, these processes may become applicable in the near future, for instance for mask repair. The physics or chemistry of this process is usually not well understood.

The scanning tunneling microscope also provides the possibility to locally stimulate chemical reactions in the presence of a reactive atmosphere, induced by local heating or directly by the energetic electrons from the tip. The possibility to perform local chemical vapor deposition (CVD) has been demonstrated for the deposition of electrically conducting nickel wires and for the deposition of very small clusters of silicon [Wong, 1995]. Cobalt, tungsten, and aluminum were also deposited. This is one of the earliest demonstrated techniques, and has resulted in useful devices for basic research. For instance, iron islands with a diameter of 20 nm and a height of 80 nm were deposited on a gold film by the local decomposition of an iron-containing gas, and used for the investigation of nanomagnetic phenomena [McCord, 1990]. The process is similar to direct deposition with a focused electron or ion beam, and a similar or better ultimate resolution should be expected. The best resolution demonstrated so far is 5 nm.

Surface modification with the atomic force microscope

The atomic force microscope (AFM, section 5.3) is sensitive to the interatomic forces between tip and sample, and can therefore be used on conducting as well as on non-conducting surfaces. The Van der Waals forces between tip and sample provide a good measure for their separation. The tip is mounted on a cantilever, and the force on the tip is measured by determining the deflection of the cantilever via the reflection of a laser beam.

When making the atomic force microscope tips conducting, either by coating with a thin metal layer [Majumdar, 1992] or by ion implantation [Kaneko, 1990], and applying a voltage between tip and sample, almost all of the lithographic techniques based on the scanning tunneling microscope can be reproduced with the atomic force microscope. The latter has the additional advantage that the distance between tip and sample can be controlled via the Van der Waals forces. This implies that non-conducting layers as well as strongly oxidized metals can be patterned. Moreover, one can first work in the atomic force microscope mode to move to the appropriate starting position with nanometer resolution and then switch to the exposure mode by applying a bias voltage for inducing the required surface modification. Although the ultimate resolution is reduced when compared to the scanning tunneling microscope, reliable lithographic patterning of surfaces becomes possible, especially when using the local oxidation technique (see below under ‘nanoelectronic devices’). A recent improvement in the performance of electron beam lithography using coated AFM tips was accomplished by introducing a double feedback loop. In addition to force feedback on the tip-sample distance, the electron current between tip and surface is kept constant by adjusting the applied voltage during writing. The resulting line structures were better in quality and also better reproducible [Ishibashi, 1998].

The local forces between the tip and the surface also provide specific surface patterning techniques which are not available or not at all reliable when using a scanning tunneling microscope. Very small gallium arsenide particles or gold clusters could be moved in a controlled way over the surface, allowing to fabricate nanodevices under ambient conditions [Junno, 1995]. When reducing the force between tip and sample, it is possible to image the sample without moving the nanoparticles. Precise nanoscale manipulation is being carried to extremes by the American scientists working on the nanoManipulator (nM) project, aimed at developing an improved, natural interface to STMs and AFMs. The nanoManipulator couples the probe to a virtual-reality interface to provide a telepresence system that operates over a scale difference of about a million to one. The person operating the manipulator can directly control the lateral position of the AFM tip using a sort of ‘joystick’, while a graphics supercomputer provides real-time shaded images and force feedback that lets the user *feel* the height of the surface. This allows the guidance of the motion of a particle during manipulation.

When applying a higher force, the atomic force microscope can be used to mechanically scratch structures with nanometer dimensions [Miyake, 1995]. Reliable patterning via lift-off techniques has been achieved by plowing grooves through the top layer of a two-layer PMMA resist. This ‘mechanical exposure’ of a resist layer has allowed to prepare chromium lines having a width down to 40 nm [Sohn, 1995]. Arrays of antidots (quantum dot holes) could be defined into compound semiconductor heterostructures¹⁸ by tapping holes with a diameter of a few nanometers into a photoresist layer with a 35-nm periodicity, followed by chemical etching. Up to 100,000 similar holes could be punched without observing any tip degradation [Wendel, 1994]. The speed of the sequential, mechanical writing techniques with the atomic force microscope remains unfortunately very low: for instance, typically 0.2 $\mu\text{m/s}$ when etching grooves. Nevertheless, an alternative scheme using a tip that receives heat pulses to scribe momentarily in resist material are being actively investigated for data storage [Mamin, 1995]. Usually the resist layer moves under the tip, similarly to conventional data storage disks. The same tip can read the pattern. The tip turns out to be very resistant to wear.

Spin-off

Just as scanning probe microscopy, scanning probe lithography can provide a clear understanding of surface phenomena in fields relevant to microelectronics. The research on an atomic hydrogen resist showed a way to increase the hot-carrier reliability of metal-oxide semiconductor field-effect transistors (MOSFETs) by an order of magnitude in a very simple way, which is important for existing fabrication technology below 0.5 micron. These results will likely ‘be readily adopted by industry’ [Glanz, 1996]. More fundamental results, such as those from the single-atom manipulation at cryogenic temperatures, may turn out to be just as important.

It is expected that research on nanoscale structures and phenomena will be greatly enhanced by capabilities for lithography at that same length scale. For instance, it turned out to be very interesting to perform electrical measurements on a carbon nanotube shown in figure 2.5.6 of 3- μm length that happened to cross two electrodes on a surface [Tans, 1997]. Moreover, it is also possible to manipulate nanotubes on the substrate by pushing them with an atomic force microscope tip, and also to cut them into segments by applying a voltage pulse to a scanning tunneling microscope tip. Likewise, it will be very valuable to access industrially relevant nanoscale molecules such as conducting oligomers or biomolecules.

In general, artificial material combinations and topographies may give insight in surface chemical and physical processes, ranging from catalysis to crystallization of proteins. This certainly requires accurate patterning control at the nm level, perhaps so accurate that it can only be provided by scanning probes.

¹⁸ structures with regions of semiconductor compounds having different compositions

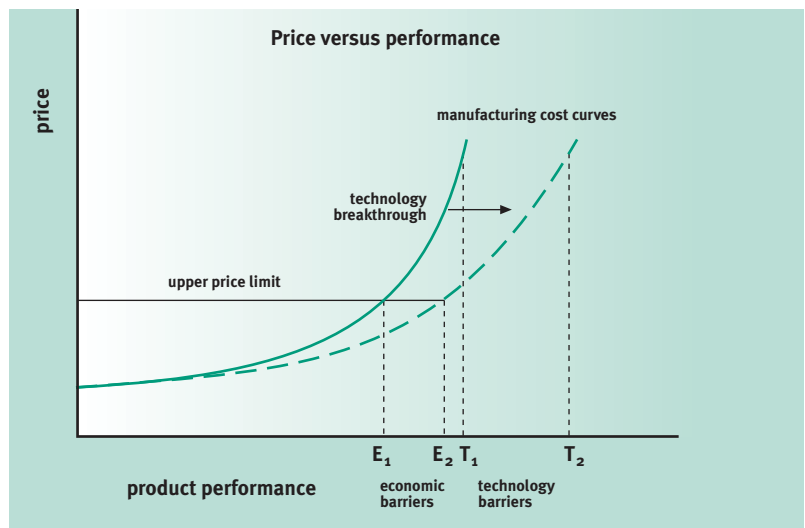
Possible commercial applications

Writing speed

At present, the serial writing of individual features with the scanning tunneling microscope or atomic force microscope can not be applied on a commercial base for the fabrication of integrated circuits, mainly because of the extremely low writing speed. Typical speed of patterning with the highest resolution in atomic hydrogen resist is a few hundreds of nanometers per second. Atom sliding takes seconds per atom. In spite of the possibility of reducing the minimum feature size down to 1 nm, drastic technological breakthroughs are required before scanning probes will be sufficiently fast and reliable for the fabrication of nanoelectronic circuits. However, it is important to note that the low throughput of electron-beam lithography as well as of the more advanced writing techniques based on scanning probe microscopes may eventually be overcome by relying on the simple imprint technique discussed in section 2.2.2. Combination of an imprint technique with scanning probe lithography for the mold preparation may possibly provide an important breakthrough for a low-cost mass preparation of nanometer scale devices (figure 2.2.24). At this point, the local oxidation of semiconductor or metal surfaces seems to offer the most reliable method to produce the required molds with nanometer resolution. It is important to note that the scanning probe microscopes can at the same time also be used to inspect the mold quality down to the atomic scale.

Figure 2.2.24

Typical cost curve for a chip manufacturing system. For a given technique (solid curve), the price of a chip will eventually increase much faster than its performance. When a minute increase in chip performance can be achieved only at a huge cost, technology barrier T_1 is encountered. On the other hand, there is also a certain maximum price the customer is willing to pay. Therefore, the economic barrier E_1 is usually encountered well before the technology barrier T_1 . Introducing a completely new fabrication technology may allow to jump to another cost curve, allowing to obtain a much better performance at the same price.

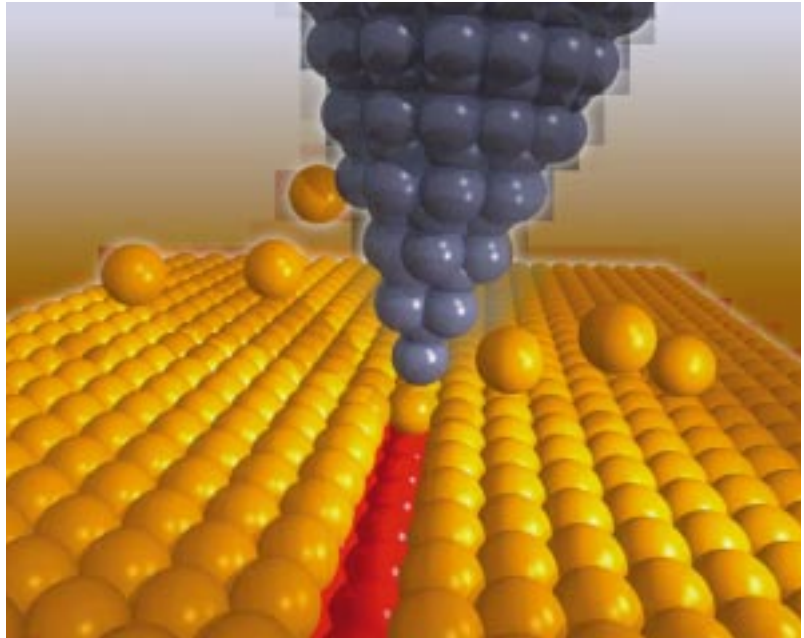


Integrated scanning probe arrays

Another possible route towards mass production of nanoscale devices may rely on the fabrication of integrated micromechanical scanning probes (micro-STMs). These contain large areas with arrays of microscopically small scanning

Figure 2.2.20

Artist's impression of scanning probe lithography with an atomic resist. See text on page 86 and further.



probes fabricated via conventional lithography [Xu, 1995]. All these micro-STMs would then write a limited part of the nanocircuit in parallel. Some work at IBM Zürich and Almaden research laboratories is aimed at scribing for data storage using this ‘multi-tip’ approach [Mamin, 1995; Pohl, 1995]. Similar work takes place at Stanford University [Minne, 1996]. By applying an voltage to an atomic force microscope tip, a resist layer can be locally modified, after which the desired patterns can be generated by selective chemical etching. Recently, they were able to read and write data at 50 kb/s using a polycarbonate sample and four-legged piezoresistive atomic force microscope cantilevers with separate integrated resistors that locally heat the tip [Micromachine devices, 1998a]. It also proved possible to write with a speed of 1 cm/s in feedback operation. A readback rate of 1.2 Mb/s of thermomechanically written pits on a rotating sample was already achieved using a single low-mass cantilever [Mamin, 1995]. For 10-nm pixels, this would mean that a bit rate of 1 Mb/s should be achievable at a storage density of over 1 Tb/in². Actually, this speed at this storage density was recently demonstrated for readout operation [Hosaka, 1997]. Significant improvement in throughput is expected in the near future by the researchers: experts postulate that arrays of 1,000 or more atomic force microscope tips will be required to achieve the data rates of magnetic disk heads [Micromachine devices, 1998b]. Figure 2.2.25 shows an artist’s impression of a multitip array. Meanwhile, an American company named Nanochip¹⁹ is already developing a memory chip based on magnetic force microscopy (MFM). Using a standard CMOS-compatible micromachine process, scanning probes are mounted 12 at a time on 45 movable stages. The tips are individually addressed via a multiplex-

19 <http://www.nanochip.com>

ing scheme. A bit of information is written on a small area by bringing one of the magnetic probes close to the surface and applying a field. The altered magnetic properties of this area can later be detected (read) by the same probe operating in constant-force mode. Within a year, the company intends to introduce a disk-drive replacement for portable applications in the form a chip-sized component that holds 250 Mbyte of data. The company has demonstrated 400 Mbyte, and even 1.7 Gbyte in write-once operation; the chips can also be cascaded. Note that this technology would make it possible to replace the present electronics paradigm based on spinning plate storage systems within ten years term. The developments at TeraStor and Quinta using near-field optical microscopy were already mentioned in section 1.2. Near-field optical (SNOM), atomic force (AFM) and magnetic force (MFM) scanning probe surface modification show immediate promise for industrial applications.

Interconnect, modify and repair

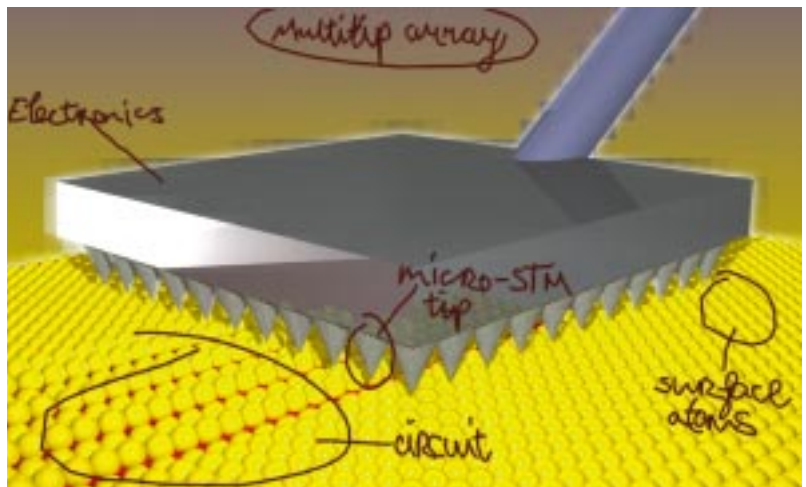
One can also take advantage of the fact that the scanning probe microscope has the unique advantage of being able to switch between the writing and the imaging mode by properly choosing the tunneling voltage or the applied force. In this way it is possible to interconnect different parts of a circuit at the nanometer level or to modify or repair existing submicrometer structures.

Nanoelectronic devices

Oxidation of silicon and transfer of the pattern by selective etching has resulted in 20-nm wide metallic wires [Kramer, 1996]. Local oxidation has been used for defining the 100-nm wide gate of a MOSFET [Minne, 1995]. By relying on a more innovative geometry, complete field-effect transistors with critical dimensions as small as 30 nm have been fabricated by the local oxidation of a passivated silicon surface [Campbell, 1995]. Higher resolution has been obtained by local

Figure 2.2.25

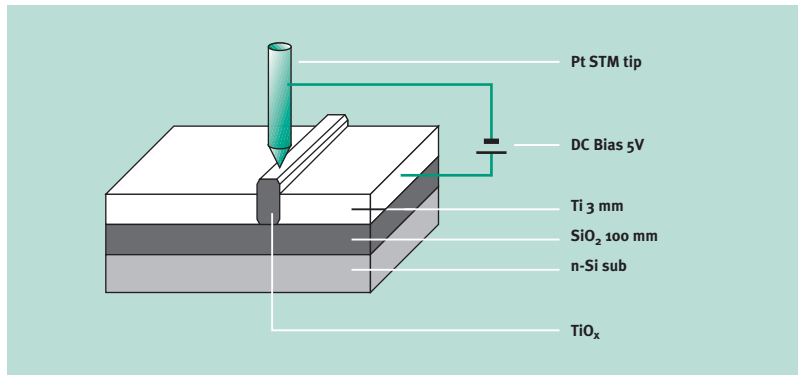
Artist's impression of a multitip array. In order to clarify the principle, the size of the surface atoms has been greatly exaggerated.



oxidation of thin metal films to create room-temperature single-electron tunneling transistors (SETs) [Matsumoto, 1996], a new type of three-terminal nanoscale devices discussed in section 2.6. Figure 2.2.26 shows how these titanium-based devices are obtained. Figure 2.6.2b reveals clear signatures of a ‘Coulomb staircase’ already at room temperature. In most cases, these devices need liquid-helium cooling in order to obtain a reliable operation. Even the tunnel barrier was created with this technique by measuring device impedance during fabrication, indicating that a feature resolution of several nanometer has been obtained. At this moment, several research groups pursue this technique further.

Figure 2.2.26

Schematic of the scanning probe fabrication process of a single-electron tunneling (SET) device: A very thin (2 to 3 nm) titanium film on a silicon wafer is locally oxidized with a metallized atomic force microscope tip or a platinum STM tip. See also figures 2.6.2 and 2.5.8. Reprinted with permission from [Matsumoto, 1996]. Copyright 1996 American Institute of Physics and American Vacuum Society.



Conclusions

The transition from microelectronics towards nanoelectronics requires the introduction of totally new production techniques. Besides self-organization of molecular structures (section 4.2), nanoscale patterning of surfaces with scanning probes may play an important role for achieving this transition. Scanning probe microscope lithography allows to prepare the individual devices which are needed to evaluate the downscaling of existing devices or to develop totally new quantum devices. When combined with a parallel processing technique such as imprinting – or alternatively, if integrated arrays of miniaturized probes can be developed – scanning probe lithography may even allow the mass production of nanoscale devices. Finally, scanning probes are suited to interconnect, modify and repair nanostructures, for instance by applying a local voltage pulse to reconnect a damaged contact that is detected during scanning-probe wafer inspection.

Currently scanning probe lithography suffers from a poor reproducibility at the nanometer level in most cases, and from a very low processing speed. Important scientific and technical efforts are needed before scanning probe lithography can be introduced in commercial production processes.

2.2.5 RESISTS FOR DEEP-ULTRAVIOLET RADIATION

*J.C. van de Grampel*²⁰

Introduction

Polymers are widely used as resists for pattern transfer to the surface in optical microlithography. Photolithography using 193-nm radiation will prove to be an important method for manufacturing integrated circuits with features below 250 nm in the near future (section 2.1.1). In designing polymers suitable as resists for optical nanolithography, several polymer properties have to be considered. For instance, the polymer should possess photoreactive groups so that images are formed upon irradiation. The polymer should be soluble in solvents that allow formation of uniform thin films during spin coating. The thermal stability should be such that the polymer can withstand lithographic process conditions. In general, materials that are thermally stable above 150°C and exhibit a glass transition temperature (T_g) above 100°C are desired. No pattern deformation should take place during pattern transfer of resist images into the substrate. Moreover the absorption characteristics of the polymer should allow uniform imaging throughout the entire resist film.

Important application characteristics of a resist are: sensitivity, contrast, resolution, optical density, and etching resistance. Sensitivity is a key characteristic in development of resist materials in photolithography. It determines the resist's efficiency in responding to a given amount of radiation. The sensitivity depends to a large extent on reactive groups in the polymer and their rate of chemical change upon exposure.

Chemical amplification can be used to improve resist sensitivity.

Chemical amplification

A chemically amplified resist is composed of a polymer with groups reactive to protons and a photoacid generator. A photoacid generator is a chemical compound supplying a proton upon irradiation. In a chemically amplified resist, this proton catalyzes reactions at the polymer, resulting in solubility differences between the exposed and unexposed regions. Unfortunately, the high sensitivity thus obtained also enhances the sensitivity towards airborne or substrate contaminants. The etch resistance to oxygen plasmas – frequently used in intermediate steps of integrated-circuit production – can be enhanced by incorporating silicon. Graft copolymers with silicon-containing branches or ladder polymers (consisting of two chains covalently bonded together) offer excellent opportunities for making oxygen-plasma-resistant resists.

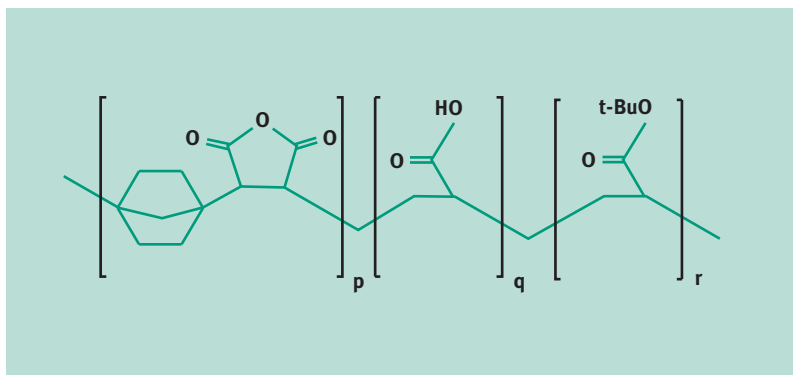
The minimum feature sizes of about 250 nm being made in the semiconductor manufacturing industry are obtained using deep-ultraviolet (DUV) radiation at 248 nm with chemically amplified resists as described above. One of the requirements of resists for 193-nm lithography (using an argon fluoride laser) is

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the absence of phenyl groups. This is necessary to obtain a very low absorption of the radiation used [Reichmanis, 1995]. This means that conventional resists such as novolacs can not be applied. Early research to design a 193-nm resist has been focused on copolymers (polymers containing various monomer units along the chain) containing acrylate or methacrylate units. However, their etching resistance appeared to be poor in comparison with novolac systems. Incorporating saturated cyclic units into the polymer chain has been shown to improve the etching resistance considerably. Using this approach, norbornene derivatives (figure 2.2.27) [Reichmanis, 1997a; Houlihan, 1997] appear to be excellent candidates for copolymerization reactions. An additional advantage is that introduction of large rings might increase the glass transition temperature. Adhesion of the resulting polymers onto silicon wafers can be improved by adding another comonomer such as maleic anhydride. Very recently, promising results have been obtained with such a resist based on a copolymer containing alternating norbornene-maleic anhydride units. Two types of these polymers were investigated; one of them is depicted in figure 2.2.27. The resist showed improved resistance to etching, improved adhesion and improved ease of development.

Figure 2.2.27

Formula of the copolymer poly-(norbornene-alt-maleic anhydride-co-acrylic acid-co-t-butyl-acrylate). This copolymer was announced as 'the first 193-nm resist that can be employed using current manufacturing technologies to support the microelectronics industry's move toward smaller and smaller design rules' [Reichmanis, 1997b].



Careful formulation of this copolymer in addition to a proper choice of dissolution inhibitor and photoacid generator has led to images with 170-nm features after deep-ultraviolet exposure and subsequent development using an aqueous base [Reichmanis, 1997a; Houlihan, 1997].

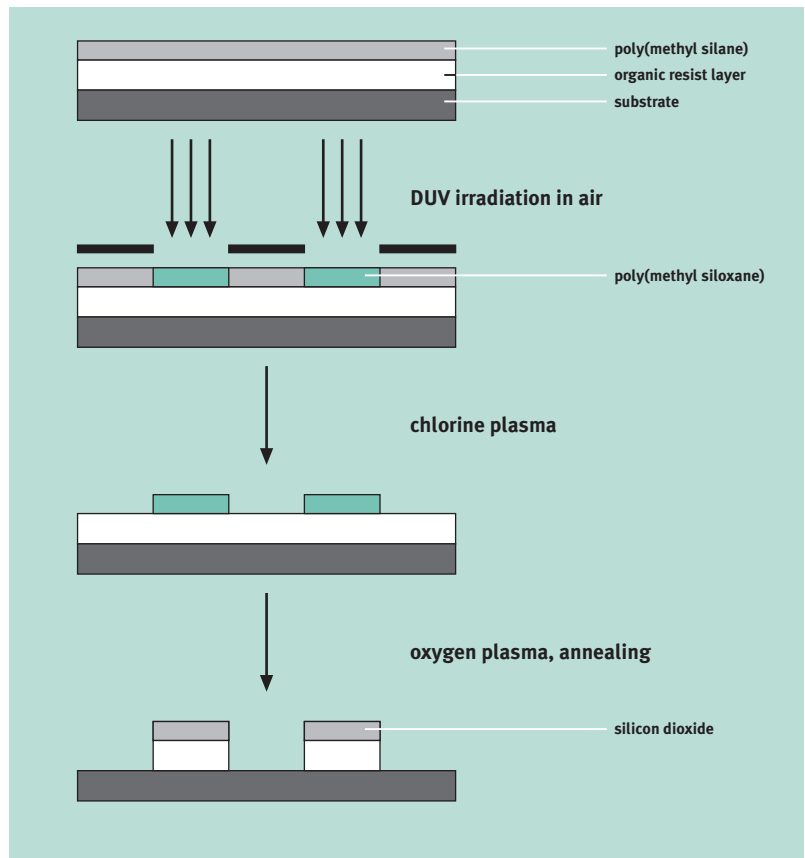
In another recent study norbornadiene²¹ derivatives were used in combination with maleic anhydride. Preliminary experiments with the resulting polymers have shown a high sensitivity and the ability to produce images with features smaller than 150 nm when using 193-nm radiation [Fréchet, 1997].

²¹ different from norbornene; two double bonds instead of one

Dry-developed resist chemistry

Besides the solution-developed methods described above, dry-developed resist chemistry forms another important strategy towards nanolithography, particularly for applications related to top-surface imaging mechanisms. It is possible to limit the image formation to the upper surface of the resist by using an organic polymer whose photoreactive groups are sufficiently absorbing to prevent the radiation from reaching the lower parts of the resist. Aromatic compounds absorbing at 193-nm can be used for lithography at this wavelength. Subsequent treatment of the resist with reactive inorganic or organic reagents can lead to regions that exhibit etching resistance towards a reactive ion environment. A recent example is the selective crosslinking of a polyvinylphenol by 193-nm radiation. Treatment of the resist with a silicon-containing vapor leads to the incorporation of silicon only in the uncrosslinked regions. Reaction with an oxygen plasma generates silica, that in turn can act as an etch mask during further processing. The resolution obtained is of the same order of magnitude as observed for the solution-developed methods described above [Kunz, 1996]. An all-dry lithographic process has been described by several authors [Weidman, 1995; Dabbagh, 1997]. In this approach plasma-polymerized methyl-

Figure 2.2.28
Schematic representation of an
all-dry lithographic process
(negative tone mode).



silane is transformed by deep-ultraviolet radiation in the presence of oxygen into a polymethylsiloxane. By subsequent plasma development and treatment, images with sub-180-nm line and space features can be transferred to an underlying organic film (figure 2.2.28).

Summary

The design of new polymeric resists for deep-ultraviolet lithography depends on the development method used. Solution development requires systems that exhibit a high optical transparency in the 193-nm region, whereas on the other hand top-surface imaging (dry-development) needs a high absorption in that region. Tailor-made resists that meet all the design prerequisites are likely to be based on the synthesis of copolymers consisting of monomers that are distinctly different from each other. It can be expected that despite all requirements that have to be fulfilled in designing a 193-nm resist, these materials will offer a way to create images with feature sizes approaching the 100-nm region.

2.2.6 RESISTS FOR ELECTRON-BEAM LITHOGRAPHY

*F.C.M.J.M. van Delft*²²

Electron-beam lithography is considered to be primarily a research tool. Although the resolution obtainable is much better than with optical production tools today, the throughput of this sequential writing technique is much too low for direct mass-scale integrated-circuit manufacturing. Therefore, the production application of e-beam writing is nowadays restricted to mask making (for the optical and x-ray production tools) and small-scale ‘direct-write’ specialties. An example of the latter will be shown below.

The electron wavelength at 50 keV is about 0.005 nm, which is far below atomic sizes and, hence, diffraction is not limiting the resolution. Electron beams can be made with a diameter of only a few nanometers. The factors limiting the resolution in electron-beam lithography are the electron forward scattering in the resist (down to a few nanometers), the electron backscattering from the substrate back into the resist (blooming effect), and the (residual) resist molecule size (several nanometers). The latter also determines the sensitivity (speed) of the resist. In order to reduce the influence of forward scattering, the resist layer should be as thin as possible, given the constraints put by the subsequent etch and/or deposition steps in the processing flow chart. The backscattering depends on the (average) atomic number of the substrate and can be suppressed effectively by using ultrathin substrates and/or by using high-contrast resists. The choice of the resist is mainly a trade-off between sensitivity (throughput) and resolution, comparable to the trade-off between film speed and grain size in classical photography.

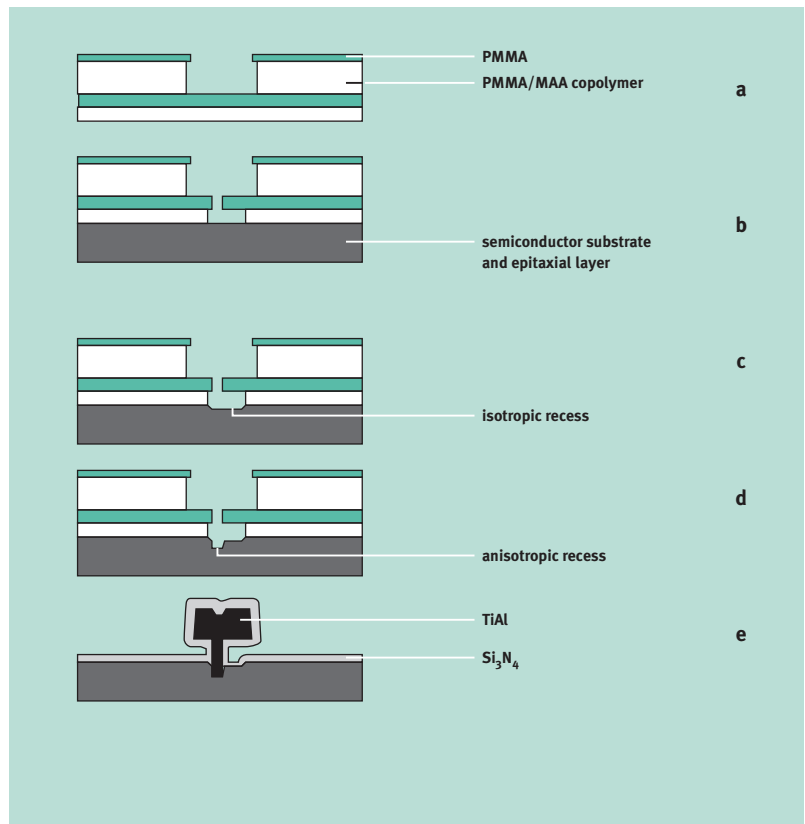
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High-resolution resists

In case resolution is the most important issue, polymethylmethacrylate (PMMA) is the most used positive tone resist. The high energy electrons perform chain scission to the polymer chain and by a proper choice of developer, the smaller fragments in the irradiated regions are selectively dissolved [McCord, 1997]. The ultimate resolution obtainable with PMMA resists has been demonstrated to be below 10 nm [Vieu, 1997]. However, this high resolution implies high doses needed for exposure and hence long exposure times. Unfortunately, PMMA has a low etch resistance in plasma etching, therefore it is mainly used in the so-called 'lift-off' technology. The material to be structured is deposited after the resist has been exposed and developed. By subsequently dissolving the resist, the material on top of it is lifted off the substrate, leaving only material on the sites where no resist was present after resist development. Resist structures with high flexibility in lift-off are obtained by combining layers of PMMA with layers of a related copolymer. As an example, figure 2.2.29 shows a processing scheme for making a power high-electron mobility transistor (PHEMT). Figure 2.2.30 shows scanning-electron microscopy (SEM) graphs of the resulting structure. Electron-beam lithography plays a crucial role for the gate definition in this fabrication process of such power amplifiers, which can be used throughout the

Figure 2.2.29

Processing steps for fabrication of a power high-electron mobility transistor (PHEMT), a power amplifier, with a 100-nm gate on gallium arsenide (GaAs). A four-layer resist stack of polymethylmethacrylate (PMMA) and a copolymer from methylmethacrylate and methacrylic acid (P(MMA/MAA)) is deposited, exposed to a low dose of electrons and selectively developed (a). After a second exposure and development of the bottom two layers of the resist stack (b), a double recess is performed: first an isotropic recess using wet-chemical etching (c), followed by an anisotropic, selective plasma etch stopping on the GaAs substrate (d). In this way, the resist profile for the so-called 'mushroom hat' of the T-shaped gate is defined (figure 2.2.30). It also permits to define the opening for the gate and the asymmetric recess extension toward the drain (for optimizing the breakdown voltage). Finally, the gate is metallized using titanium aluminum alloy (TiAl), the polymer resin with the alloy on top is removed (lift-off), and silicon nitride is deposited for passivation (e). Reprinted with permission from [Frijlink, 1997]. Copyright 1997 Elsevier Science.

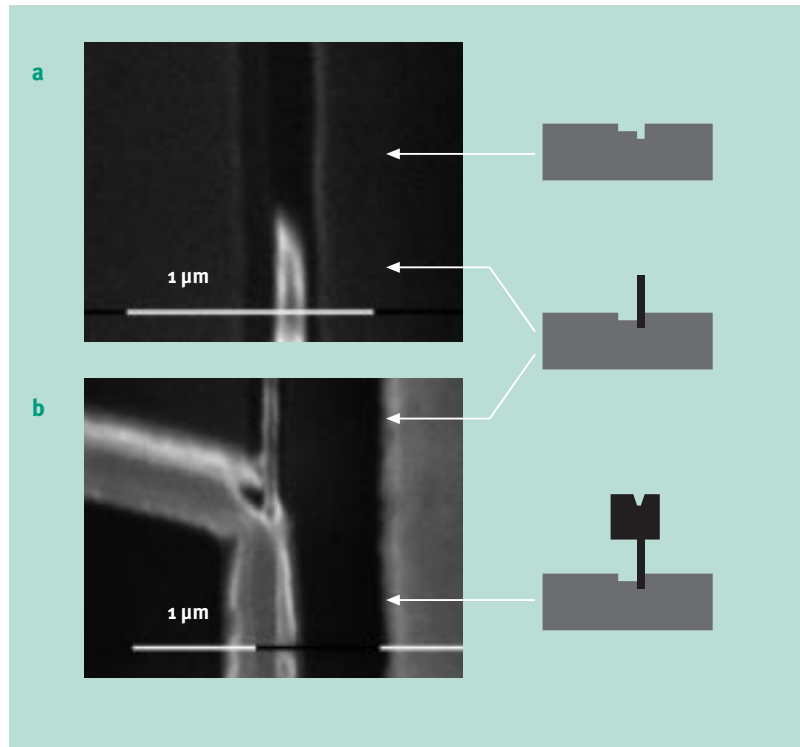


millimeter-wave spectrum, as well as in very low noise amplifiers. The process shown here permits amplification up to the W-band [Frijlink, 1997]. Such PHEMT's are to be used in, for instance, telecommunication applications such as the Global System for Mobile communications (GSM).

Research is being performed on other high-resolution organic resists [e.g., Prins, 1998] and inorganic resists. For instance, aluminum fluoride (AlF_3) allows details down to 1 nm to be resolved, but very high doses are needed. At present, PMMA and its derivatives still seem to be the best choice for general use.

Figure 2.2.30

Scanning electron microscopy (SEM) graphs of a mushroom gate (top view) produced according to figure 2.2.29 (without silicon nitride passivation). Figure (a) shows the asymmetric double recess (dark lines at the top) and the gate foot (lighter line at the bottom). The size of the gate foot is 115 nm. The two different parts of the recess are clearly visible, the deeper part being darker. (b) This view was obtained by mechanically ripping off part of the gate to the left. On the right, the source contact is visible. The corresponding cross sections are shown in the drawing on the right. Reprinted with permission from [Frijlink, 1997]. Copyright 1997 Elsevier Science.



High-speed resists

For applications where throughput is the most important issue, for instance in mask fabrication for 5:1 projection deep-ultraviolet lithography, a resist called EBR-9 can be used, which offers an ultimate resolution of 200 nm [McCord, 1997].

Novolac resists used as electron-beam resists

The novolac resists commonly used in mid-ultraviolet lithography [Dammel, 1993] can also be used in electron-beam lithography. The ultimate resolution typically stays above 200 nm. This limit is determined by the minimum residual polymer size and not by the type of exposure.

An acid-catalyzed positive-tone novolac resist has been shown to give details

with 70-nm resolution by provoking a negative tone behavior at high doses (cross-linking instead of chain scission) [de Koning, 1995]; note that this result is in line with the above-mentioned trade-off between sensitivity and resolution.

Deep-ultraviolet resists used as electron-beam resists

The newly developed chemically amplified deep-ultraviolet resists discussed in section 2.2.5 are also sensitive to high-energy electrons. The (economically driven) strong research-and-development-efforts of resist-producing companies in optimizing these deep-ultraviolet resists are currently causing electron-beam lithographers to implement more and more deep-ultraviolet resists in their processes. The most favorable deep-ultraviolet resists nowadays are based on a polyhydroxystyrene (PHS) backbone and a photoacid generator; they can be used as sensitive positive or negative tone resists [Allen, 1997]. Their resolution limit for electron-beam lithography is typically around 60 nm [Macintyre, 1997]. They show an intermediate behavior in terms of resolution and sensitivity compared to the PMMA and EBR-9 extremes. Their plasma-etch resistance is much higher than that of PMMA.

The use of deep-ultraviolet resists in electron-beam lithography also opens up the possibility to expose the same resist layer in both a deep-ultraviolet stepper and an electron-beam machine before development (the so-called 'mix and match' technology). In this way, large surface areas are being exposed with medium-to-low-resolution by the fast deep-ultraviolet stepper, whereas the higher-resolution details are being exposed by the accurate but slowly scanning electron beam. The overall result is an on-average acceptable writing time with higher-resolution details in the most critical areas of (for instance) an integrated circuit.

2.2.7 LIMITATIONS OF DRY ETCHING

*F.C.M.J.M. van Delft*²³

Introduction

Much of the innovation in electronics will occur by the incorporation of new materials into both existing and new nanoscale devices. Dry etching techniques such as plasma etching (PE), reactive ion etching (RIE) and reactive ion beam etching (RIBE) have originally been developed as structuring techniques for micrometer-scale silicon-based devices. They feature controlled side wall profiles, high etch rates and high etch selectivities. The successful application of these techniques to new materials in the production of nanoscale devices requires knowledge about the etch mechanisms of both the materials to be etched and their most suited masking layers. Examples of new materials in (nanoscale) devices are magnetic multilayers in thin film recording heads, oxidic

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multilayers in ferro-electric memories, oxidic high-temperature superconductors in SQUIDS (Superconducting QUantum Interference Devices) and III-V compound semiconductors such as gallium arsenide (GaAs) and indium phosphide (InP) in single-electron tunneling transistors (SETs) and field-effect transistors (FETs) (section 2.6).

Model of reactive ion etching

Like microcontact printing, dry etching is a pattern transfer process. Before etching, the wafer has been coated with (intermediate mask layers and) a resist, which has been patterned using for instance electron-beam lithography (section 2.2.6). The reactive ion etching process can be described as a surface reaction with neutral adsorbing gas molecules (or radicals), activated by fast particles coming from a plasma. This mechanistic model also applies to

Table 2.2.2

Four basic etch mechanisms (see also figure 2.2.31).

etching type	rate-determining step (rds)	applies e.g. to	characteristics	result
I	etch product sputtering	magnetic alloys and multilayers containing iron or cobalt, in chlorine-containing plasmas at low temperatures	volatile etch products not easily formed; low, temperature-independent etch rates	tapered side walls due to etch product redeposition (figure 2.2.32)
II	etch-product thermal desorption	as I , at elevated temperatures	etch rate rises with temperature	steeper side walls due to diminished etch product redeposition (figure 2.2.33)
III	mechanically activated adsorption or surface reaction	silicon in fluorine- or chlorine-containing plasmas and photoresists in oxygen-containing plasmas at low temperatures and low pressures	easy formation of volatile etch products [van Delft, 1997]	– Vertical side walls; no etch product redeposition (figure 2.2.34) – tapered side walls due to mask width loss – bottle-shaped mask undercutting due to fast-particle scattering
IV	full thermal activation of all steps	as III , at elevated temperatures and high pressures	fast isotropic etching, etch rate rises with temperature (until chemisorption stops)	– (isotropic) mask undercutting as in wet-chemical etching – vertical side walls possible when depositing protective polymer coatings

ion-beam-assisted etching and tribochemical etching (chemical reactions provoked by friction and wear). In plasma etching and reactive ion etching, the wafer to be etched is placed on the cathode of a parallel-plate reactor. The plasma that is induced between the plates using a radio frequency (rf) source acts as a source for charged and neutral high-energetic particles (and radicals). Basically, three consecutive reaction steps can be discerned in reactive ion etching: etch reactant chemisorption, surface reaction and etch product desorption. It is assumed that these steps are activated both thermally and mechanically by the fast particle impacts [van Delft, 1996]. The model discerns four basic types of etching (table 2.2.2). The resulting etch profiles are determined by the rate-determining step in the etch mechanism. Figure 2.2.31 shows an algorithm to determine what type of etch mechanism applies to a specific new material. In the model, the mechanisms are coupled to certain etch profiles underneath a mask that is assumed to be perfect and non-etching [van Delft, 1998]. Below the first row of etch profiles in figure 2.2.31, possible non-ideal etch profiles are also shown.

Figure 2.2.31

Algorithm for determining the etch mechanism and profile for a given new material in reactive-ion etching. The model input consists of some parameters known a priori (the boiling points of the expected etch products (T_b) or their heats of vaporization (ΔH_{vap}) and the gas constant R and some parameters to be measured during test runs (the equilibrium surface temperature during etching (T_{eq}) and the etch rate as a function of this temperature ($r=f(T)$) (see also table 2.2.2). Reprinted with permission from [van Delft, 1998]. Copyright 1998 Elsevier Science.

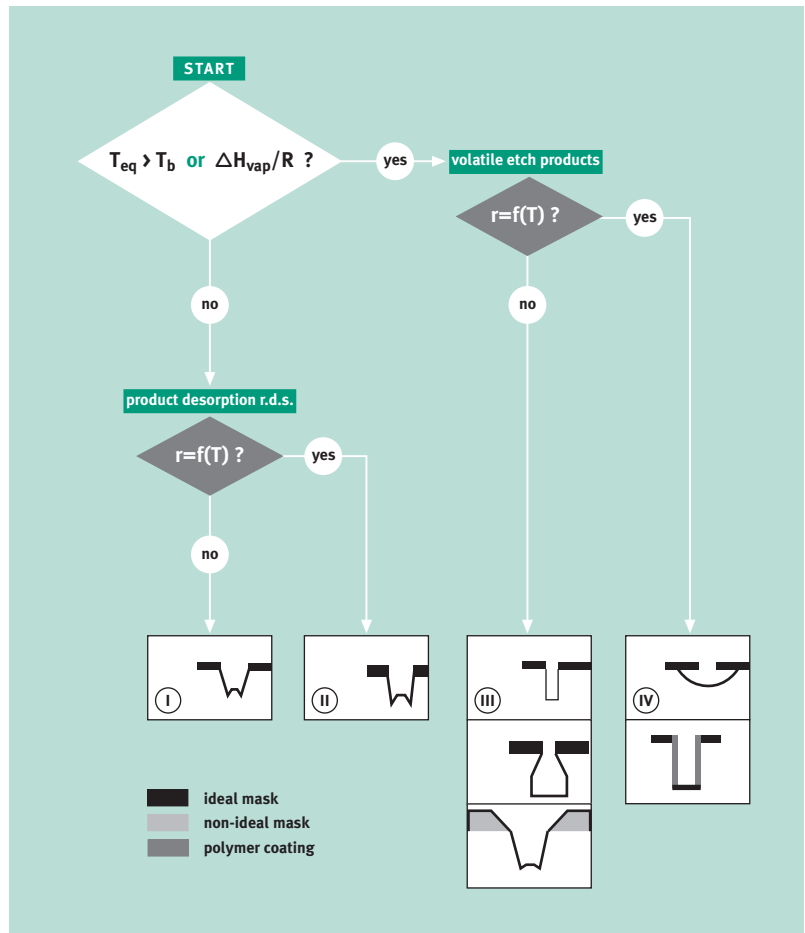


Figure 2.2.32

Scanning electron microscope (SEM) graph of a cobalt alloy feature with tapered side walls and with trenches at the bottom etched in a 0.04-mbar HCl plasma at 400 W at low temperature (type-I etching). As indicated in the black bar, the length of the white bar below equals 10 μm .

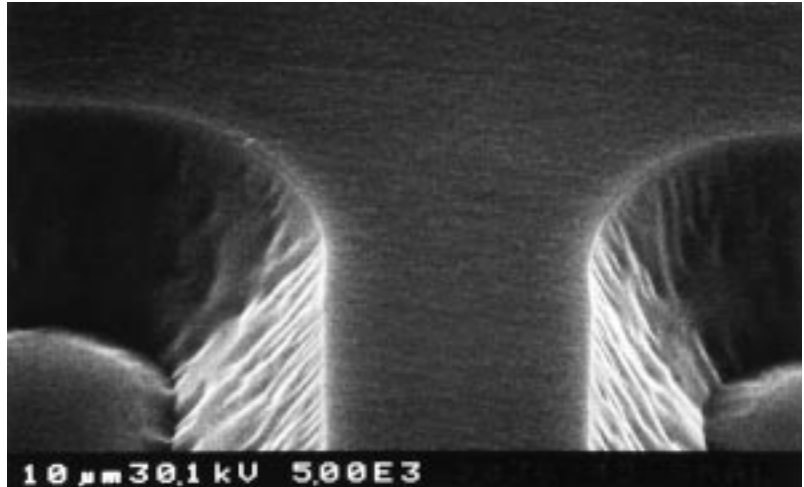


Figure 2.2.33

Scanning electron microscope (SEM) graph of a cobalt alloy with steeper side walls etched in 0.1-mbar HCl plasma at 400 W at high temperature (type-II etching). An alumina etch mask residue is still present on top of the structure.

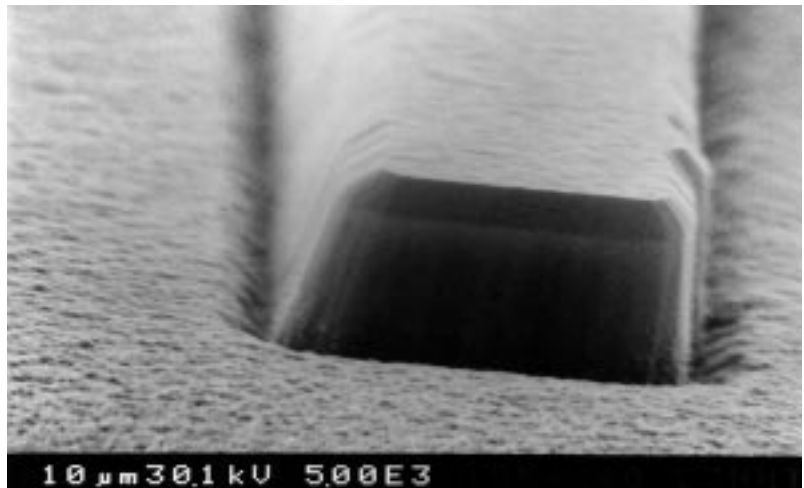
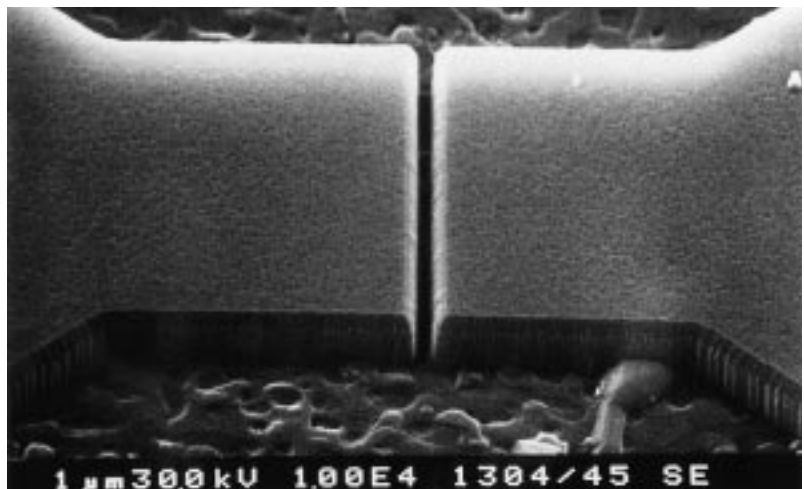


Figure 2.2.34

Scanning electron microscope (SEM) graph of a resist (AZ1512) etched in a 0.01-mbar oxygen plasma at 100 W using a germanium mask, showing vertical side walls obtained at low temperatures and low pressures (type-III etching). Reprinted with permission from [van Delft, 1997]. Copyright 1997 Elsevier Science.



Type-I and -II etching occur for instance in chlorine containing plasmas for iron and cobalt alloys (used in magnetic structures such as disc drive heads). Type-III etching occurs for patterning of silicon in fluorine and chlorine-containing plasmas and for resists in oxygen-containing plasmas. Although vertical side walls can be produced, this mechanism may still result in imperfect features: mask width loss may lead to tapered side walls, while fast particles coming in non-vertically due to scattering in the gas phase (e.g. at higher pressures) and on the evolving side walls can induce bottle-shaped mask undercutting. The III-V compound semiconductors exhibit a behavior intermediate of that of silicon and iron. At low temperatures, tapered profiles are obtained through type-I and type-II etching; at high temperatures, isotropic etching of type IV is observed; type-III etching, resulting in vertical side walls, is possible in a narrow temperature region [van Delft, 1996]. Vertical side walls may also be obtained in type-IV etching by adding components to the plasma gas feed that deposit protective polymer coatings. Such coatings are still sputtered away from the bottom of the profile, but they do protect a vertical side wall, as indicated in the second profile for type-IV etching in figure 2.2.31.

In many cases, plasma etching is intended to produce vertical side walls. The biggest challenge in developing a dry etch process for a new material is to find a process with volatile etch products and high etch rates in order to obtain such vertical side walls [Giesbers, 1997]. Unfortunately for etch researchers, most elements in the periodic table do not easily form volatile etch products which survive in plasma environments. In silicon technology nowadays higher etch rates, higher selectivities and lower damages can be obtained by introducing high-density plasma sources such as electron cyclotron resonance (ECR) and inductively coupled plasma (ICP) sources. These yield plasmas with more radicals and higher ion-current densities while retaining lower particle energies, because the accelerating voltage is decoupled from the plasma-generating power [Joubert, 1998]. As can be deduced from the above mechanistic considerations, however, such new types of sources offer no improvement in getting another type of etch mechanism for a new material, as long as the etch products are not volatile.

Nanoscale etching

Etching nanometer- instead of micrometer structures does not significantly alter the surface chemist's considerations shown above, as long as layer thicknesses are scaled down with the lateral dimensions. Patterns with a 9-nm feature diameter have been fabricated [Tada, 1998]. A process yielding a 5- μm deep trench at 1 μm width – at best – cannot be expected to do better than 50 nm depth at 10 nm width. In general, one would prefer the ability to etch nanostructures with vertical side walls. Clearly, type-I and type-II etching will be unsuitable for this purpose. However, type III and IV may require elevated temperatures that can

not be applied to every material. For example, magnetic materials comprising nanometer-thin layers would start to mix under such thermal conditions, resulting in loss of their unique properties. Another limitation will arise from statistical noise: although the basic chemistry stays the same, the walls will be relatively rough when the lateral dimensions come down to a few atomic distances. For deep narrow structures, problems concerning diffusion and ‘microloading’ should be tackled. These effects occur when the local reaction rate becomes limited by diffusion because of a local depletion of the reactants and/or accumulation of etch products. For micrometer-scale silicon etching, these problems are adequately addressed in the literature [Boernig, 1998].

For structuring materials which are highly sensitive to the oxygen content of the remaining oxide – such as high-temperature superconductors – sputter-etching in argon plasmas is favored despite the low etch rates and the tapered side walls [Gijs, 1991]; or alternatively, patterning is performed by locally upsetting the oxygen content on purpose (oxygen implantation) instead of etching [Hollkott, 1998]. Both procedures allow patterning of 100-nm details.

Conclusions

The successful application of dry etching to new materials in the nanoscale regime mainly depends on the ability to design a plasma chemistry which yields volatile etch products only. If this is not possible, other structuring procedures should be investigated such as implantation or lift-off (section 2.2.6), or one should be satisfied with low etch rates, low selectivities and tapered profiles.

2.2.8 CONCLUSION

A. ten Wolde

This section has shown that there are numerous ways to achieve nanostructuring of surfaces using lithography. The industry has not yet chosen for one of these to manufacture the first generation of nanoelectronic devices. Four consortia, in which ASML Veldhoven participates, have been founded to investigate the various options [Smit, 1998]. The main characteristics of the techniques discussed are listed in table 2.2.3. The choice will depend on the critical factors rather than on the achievable resolution.

patterning technique	resolution (nm)	critical factors	status	remarks
deep-ultraviolet	130 (70)	optical imaging	development	pushing the limit
ion-beam projection	< 100 (35)	mask, optics, stitching	option	relatively cheap
extreme-ultraviolet	< 100 (35)	optics, mask, sources	option	promising
x-ray proximity	30 (25)	mask, optics, sources	option	so far no mask commercialization
SCALPEL	80 (35)	stitching, mask, blur	option	promising
microcontact printing	50 (20)	limited patterns, wear	lab phase	pattern transfer technique
atom lithography	80 (20)	limited patterns	lab phase	
scanning probes	0.1	speed	lab phase	parallel approach under investigation
electron-beam (serial writing)	5 (1)	speed	tool	e.g., for mask fabrication
dry etching	10	resists	tool	pattern transfer technique

Table 2.2.3

The main characteristics of the techniques discussed. The listed resolutions have been obtained or are considered achievable (bracketed). With deep-ultraviolet lithography, the optical approach will ultimately reach its limit. The techniques labeled 'option' are candidates for the mass manufacturing of chips with features below 100 nm. Various other approaches are still in the lab phase, but may be applicable in the future. Electron beam lithography using serial writing is too slow for the mass manufacturing of chips, but is a very useful tool for mask fabrication. Dry etching and microcontact printing are pattern transfer techniques.

2.3 QUANTUM STRUCTURES FABRICATED WITH EPITAXIAL GROWTH

*P. Van Daele*²⁴

Selective epitaxial growth

Selective epitaxial growth (SEG) is a technique based on the fact that the growth of high-quality films on crystalline substrates is strongly dependent on structural properties of the substrate such as the lattice structure, the crystallinity and the morphology. ‘Epitaxial’ means that the lattice structure of the substrate is continued in the deposited layer. By creating areas on a substrate with optimal properties (perfect crystallinity) and regions where these properties are lost, a structured film is obtained during layer deposition. A variety of techniques using deposition and ‘bottom-up’ growth rather than ‘top-down’ patterning using lithography are used to fabricate films, wires, pyramids and disks of nanometer dimensions (so-called low-dimensional structures). An advantage of these techniques is that no patterning need be done on the deposited layer. In this way some of the problems associated with top-down techniques can be avoided, such as degradation of the nanostructures due to heating. The edges of nanostructures are especially sensitive, which can lead to unstable structures.

In the case of selective epitaxial growth, patterning does take place, but before deposition. The substrate can, for instance, be pre-patterned using electron-beam lithography and prepared for selective epitaxial growth by depositing a layer with the desired crystal structure, crystallinity and morphology (a ‘definition’ layer).

This section deals with low-dimensional structures in compound semiconductors. It should be mentioned that they can also be constructed using other materials. For instance, quantum dots from cobalt or copper can be fabricated using selective epitaxial growth on prepatterned substrates. On the other hand, the formation nanostructures using high-temperature superconductor material ($\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$, abbreviated as YBCO) is rather difficult.

Quantum confinement

During the last two decades there has been enormous research activity on structures of dimensions so small that quantum confinement (figure 2.3.1) determines the properties. This activity is partly due to the constant improvement of techniques such as molecular-beam epitaxy (MBE) and metal-organic vapor phase epitaxy (MOVPE, often referred to as metal-organic chemical vapor deposition (MOCVD)). With these techniques, the epitaxial growth of very thin (typically smaller than 20 nm) crystalline layers can now be easily realized. Confinement in more than one dimension will significantly modify the band structure of the semiconductor system, which has a strong impact on the electron density of states. Figure 2.3.1 illustrates the changes of the density of

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states as the dimensionality of the structure is decreased. The introduction of quantum confinement in semiconductor structures revealed numerous interesting physical effects and resulted in a strong improvement of several electronic and optoelectronic devices. Extending the quantization to two dimensions (quantum well wires) or three dimensions (quantum boxes, also referred to as quantum dots) is expected to offer some very interesting perspectives and bring along new physical phenomena. The idea of low-dimensional semiconductor structures was postulated in 1980, when it was calculated that gallium arsenide (GaAs) quantum wells with a thickness below 10 nm should allow extremely high electron mobility [Sakaki, 1980]. In atoms, the energy levels are discrete because the electrons are confined by the Coulomb potential.

Due to the modified density of states, the carriers are more concentrated in energy levels useful for laser action. As a result the laser efficiency increases as the dimensionality of the semiconductor is decreased [Weisbuch, 1990], as shown in figure 2.3.2.

Figure 2.3.1

Quantum confinement: the energy levels that an electron may assume can be severely limited by structural dimensions. Shown is the density of states ρ versus the energy E for a bulk semiconductor (left) and for semiconductor structures with quantum confinement in one (quantum film or well), two (quantum wire) and three dimensions (quantum box or dot), respectively. Compared to the parabolic shape for bulk material, where all energies are allowed, the density of states becomes more peaked as it transforms into step-like, reciprocal square root and delta-function shapes as the dimensionality of quantum confinement is increased. Reprinted with permission from [Asada, 1986]. Copyright 1986 IEEE Lasers and Electro-optics Society.

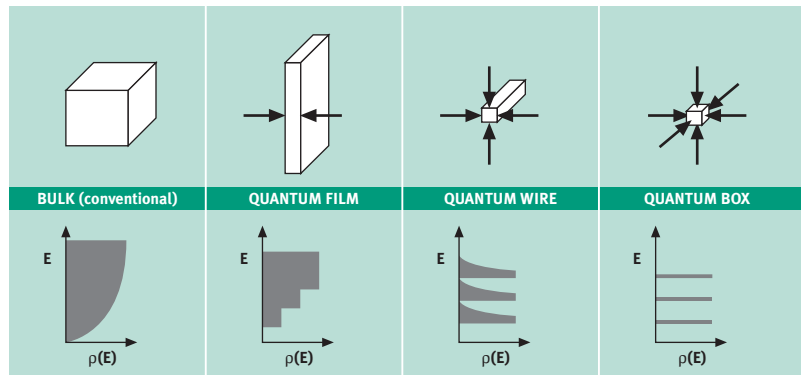
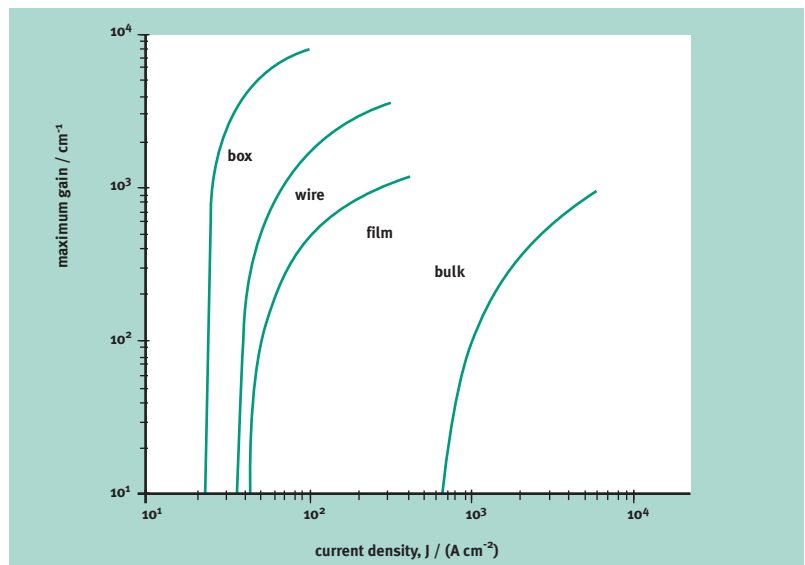


Figure 2.3.2

Calculated laser light amplification (gain) curves versus the input current for low-dimensional compound semiconductor lasers. Reprinted with permission from [Asada, 1986]. Copyright 1986 IEEE Lasers and Electro-optics Society.



In practice however, size fluctuations of the quantum wires and dots result in inhomogeneous broadening of the gain spectrum and can completely override all the advantages related to two- and three-dimensional quantum confinement. This requirement for very uniform quantum wires or dots creates some major challenges for fabrication and explains the remaining difficulties in clearly confirming their predicted characteristics. Compared to quantum-well structures, the reduction of the active layer dimensions in the directions perpendicular to the growth direction is far more difficult to obtain and nowadays a huge variety of different approaches are investigated.

Fabrication of low-dimensional structures

Among the wide variety of techniques studied for the growth of low-dimensional structures, one can distinguish between in-situ and ex-situ techniques. In the ex-situ techniques, the low-dimensional structure is defined after the growth of a planar quantum well (figure 2.3.3). These techniques include wet and dry etching with possible regrowth [Notomi, 1994], lateral intermixing, disordering [Hämisch, 1993] and locally induced stress [Tan, 1993].

Figure 2.3.3

Different proposed ex-situ schemes to fabricate low-dimensional structures by applying wet or dry etching techniques. Dark arrows indicate wet etching techniques, the gray arrow (e) indicates a dry etching process. The schemes start with an embedded quantum well grown by epitaxial techniques. Source: [Vermeire, 1995]

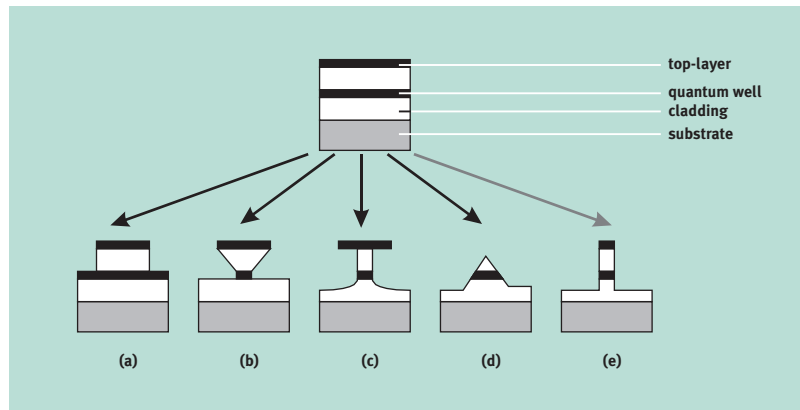


Figure 2.3.4

Fabrication of low-dimensional structures using epitaxial growth on off-oriented substrates. The substrate surface is polished at a small angle from one of the lattice axes, leading to the formation of small steps on the surface that consist of small pieces of crystal planes oriented along the lattice axis. The resulting tilted periodic structures of pieces of materials of varying composition are either plain fractional layer superlattices (FSL), tilted superlattices (TSL) or serpentine superlattices (SSL). Source: [Vermeire, 1995]

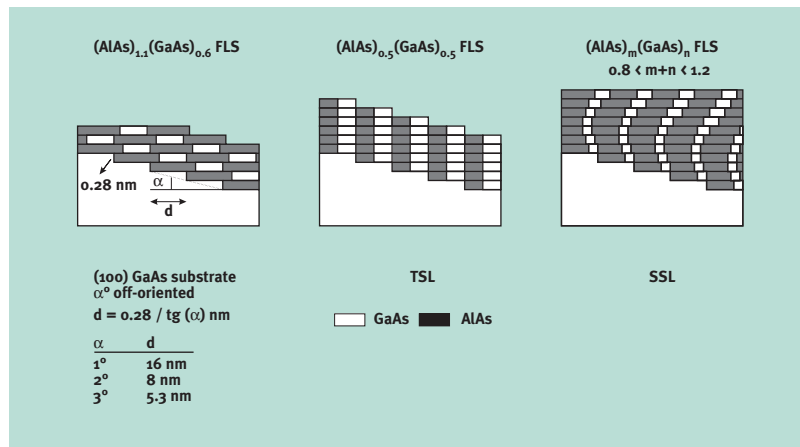


Figure 2.3.5

Schematic representation of non-planar and selective epitaxy making quantum wires as realized in several laboratories: (a) V-grooves; (b) platform (mesa) in (110) direction²⁴; (c) mesa in (110) direction; (d) an oxide channel (a strip-shaped opening in the applied oxide layer, for selective epitaxial growth) in (110) direction; (e) oxide channel in (111) direction; (f) oxide channel on (111) substrate and (g) growth of a pair of quantum wires, oriented perpendicular to the plane of the drawing. (110), (111), (100) etc. denote different directions in the crystal structure. Source: [Vermeire, 1995].

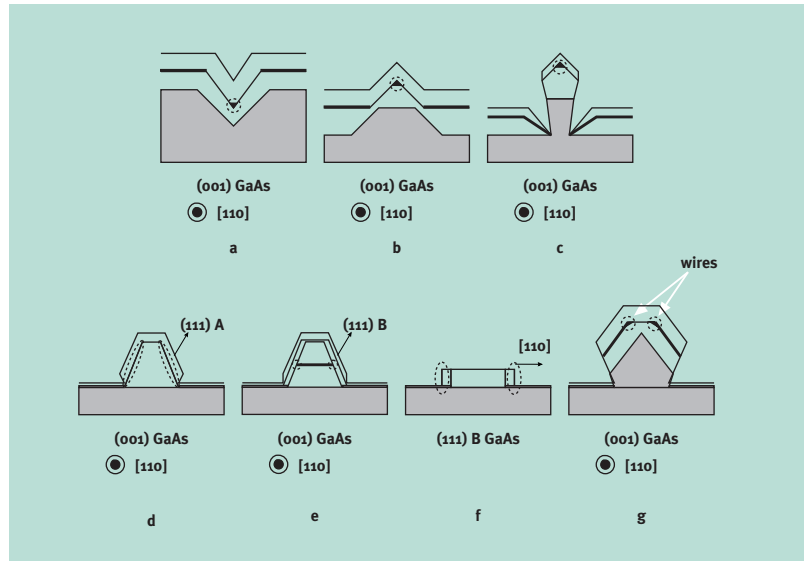
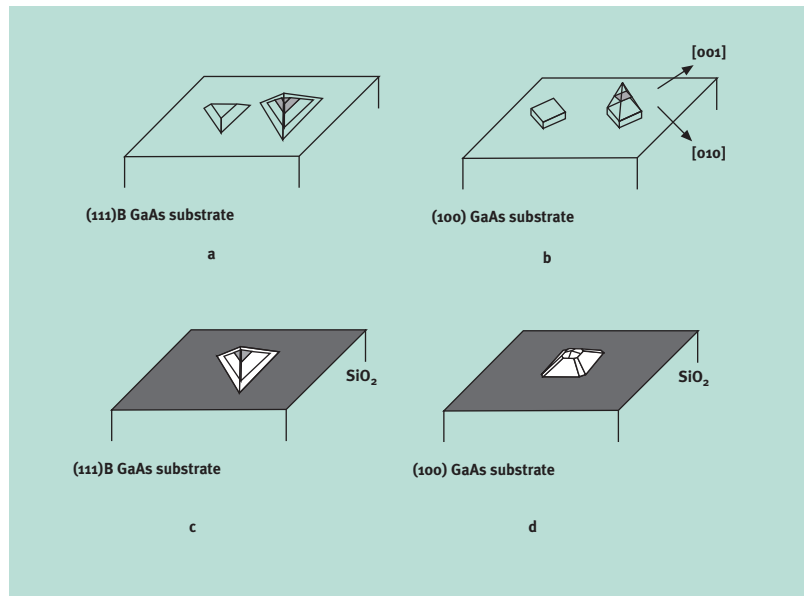


Figure 2.3.6

Schematic representation of non-planar and selective epitaxy making quantum dots: (a) pyramid shaped mesa on a (111) GaAs substrate; (b) cubic mesa etched in a (100) substrate; (c) pyramid formed by selective epitaxial growth on a triangular opening; (d) and on a square opening in an oxide mask. The shape of the formed structure is determined by the crystal plane growth velocities. The planes that grow slowest – mostly (111) or (311) planes – appear on the outside of the formed structure. Due to the orientation of these planes in III-V semiconductors, a pyramidal shape will appear automatically. Its precise form depends on the shape of the opening in the oxide mask, while its quality depends on the structure and on the growth parameters. Source: [Vermeire, 1995].



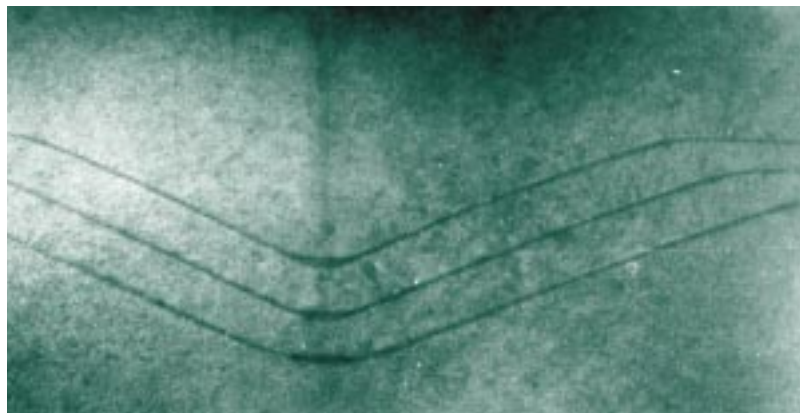
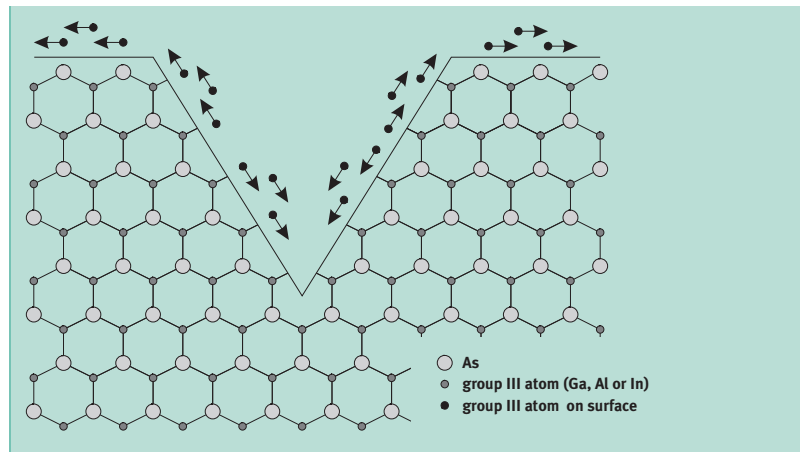
The single-step growth techniques in which the wires and dots are defined in situ during epitaxial growth are most interesting for the study of optical properties of quantum wells and quantum dots. In this case there is no need for fine-line lithography, there are no exposed facets and good quality interfaces can be obtained. Some of these more successful techniques are the growth on off-oriented substrates for the realization of plain fractional layer superlattices (FLS), tilted superlattices (TSL), serpentine superlattices (SSL) [Fukui, 1987], self-organized growth on high-index surfaces [Ploog, 1992], macrosteps during non-planar growth on off-oriented substrates [Colas, 1989], and selective epitaxial

growth on gallium arsenide [Fukui, 1989] and indium phosphide (InP) [Galeuchet, 1991]. Some of these techniques are illustrated in figure 2.3.4. Other techniques include non-planar growth and selective epitaxial growth (epitaxial growth restricted to selected areas of the surface) as shown in figure 2.3.5 in the case of quantum wires and figure 2.3.6 in the case of quantum dots.

Among all of these techniques, non-planar growth on V-grooved substrates [Kapon, 1992] and on submicron gratings [e.g., Vermeire, 1992] are probably the most successful, especially for investigating optical properties and for the creating quantum-wire lasers. Since gallium, aluminum and indium all diffuse differently along the surface during the process, accumulation of certain of these group-III materials will occur at the bottom of the V-groove. Aluminum sticks more easily to the surface, whereas gallium can diffuse over larger distances to the regions where it likes to be most. When growing aluminum gallium arsenide (AlGaAs), this leads to a relatively high aluminum content in the side walls of the V-groove and to a crescent-shaped region on the bottom with larger thickness, a higher gallium content and less aluminum (figure 2.3.7). In this way

Figure 2.3.7

(a) Schematic representation of surface diffusion effects during non-planar metal-organic vapor phase epitaxial (MOVPE) growth and (b) a transmission electron microscope (TEM) photograph showing a cross-section of three gallium arsenide (GaAs) quantum wells grown in between AlGaAs-barrier layers on a gallium arsenide substrate with V-grooves. The thickness of the quantum wells (dark lines) is 2.5 nm and the crescent-shaped quantum wires at the bottom of the groove can clearly be seen. Although each wire is connected with a quantum well, it behaves like a wire. Source: [Vermeire, 1995].



quantum wires can be formed at the bottom of the V-grooves. The diffusion process during metal-organic vapor phase epitaxial growth is very well controlled and this technique has already lead successfully to laser operation with a low threshold [Simhony, 1991]. The process starts with the fabrication of sub-micron gratings with periods between 600 and 800 nm, realized by holographic lithography and wet chemical etching. In an interesting alternative for grating fabrication, 100-nm wide silica stripes were defined on a gallium arsenide substrate with a 200-nm period [Tsukamoto, 1992]. Triangular prisms are formed during the selective growth of gallium arsenide; a 200-nm pitch grating is defined during the epitaxial growth, resulting in very uniform gratings with smooth side walls.

The group-III atom itself determines surface diffusion properties [Vermeire, 1993]. Both the aluminum-containing reactant species and the aluminum atom itself are very reactive, resulting in a low surface mobility compared to gallium [Karam, 1991]. The different surface diffusion properties of aluminum and gallium lead to the formation of a crescent-shaped quantum wire, but if thicker AlGaAs layers are grown on gratings, vertical columns of gallium-rich material are formed along the grooves of the grating during the bulk growth process [Vermeire, 1992]. These columns behave as quantum wells. An example is shown in figure 2.3.8. Photoluminescence measurements of vertical AlGaAs layers reveal rather intense, polarization-dependent light emission. Although the grating can also induce some polarization anisotropy, the shifted peak of the emission spectrum is an especially strong indication for lateral confinement. Such a polarization dependence has also been observed for fractional layer superlattices [Fukui, 1991] and analogous behavior was found during photoluminescence excitation measurements on quantum wells [Tsuchiya, 1989]. The effects are explained by the polarization-dependent selection rules for the transitions in quantum wells.

Figure 2.3.8

Scanning electron microscope (SEM) picture of a cross-section showing vertical AlGaAs quantum wells (two narrow straight stripes on the enlargement on the right hand side of the photograph) realized using metal-organic vapor phase epitaxial (MOVPE) growth of $1\ \mu\text{m}$ AlGaAs on a grating. The stripes are sandwiched between barrier layers with a higher aluminum content. The crescent-shaped structures are an artifact from the imaging procedure. Source: [Vermeire, 1995]

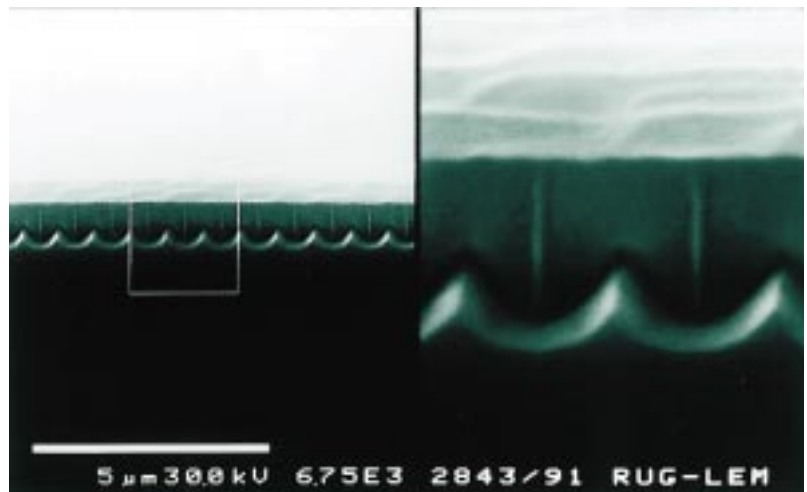
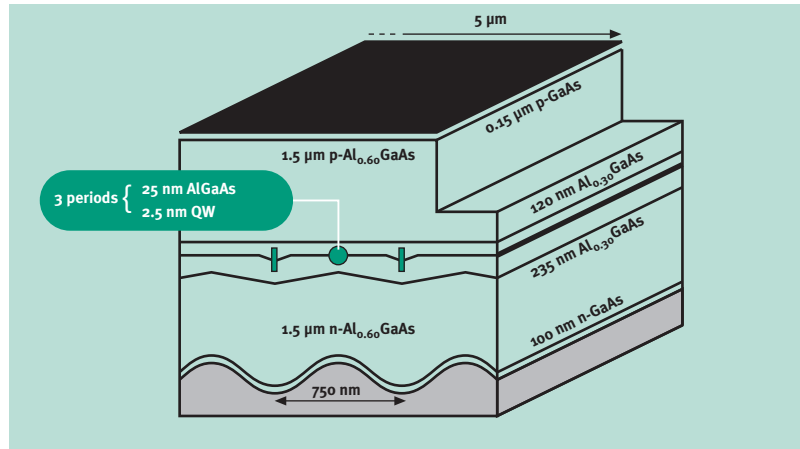


Figure 2.3.9

Schematic representation of a layer structure that may be used to fabricate a highly efficient laser diode. It is grown on a grating with submicron period etched in a substrate. Surface diffusion of gallium and aluminum results in an array of vertical quantum wells and crescent-shaped quantum wells. Reprinted with permission from [Vermeire, 1993]. Copyright 1993 The Royal Society.



The combination of vertical quantum wells and crescent-shaped quantum wires can have some very interesting applications. An example that could lead to a diode laser is shown in figure 2.3.9. The vertical quantum wells operate as efficient collection channels for carriers because they can guide carriers to the quantum wires [Walther, 1992].

The different techniques described here very briefly indicate the wide variety of techniques that can be used to grow low-dimensional structures in compound semiconductors. Because they offer superior optical qualities, uniform arrays of nanometer-sized buried quantum dots produced by self-organized growth are now a favored option for applications in semiconductor devices [Nötzel, 1996]. A recent step forward was made by the combination of patterning and self-organization [Nötzel, 1998]. Careful tuning of the different processing steps involved, such as etching, lithography, and epitaxial growth, is absolutely necessary to overcome the problems of non-uniformity and dimensional variations in the structures fabricated. Further investigation into these problems will be required for the use of such structures in devices and components. However, research in this field is justified in view of the potential improvements in characteristics and performances of existing devices and components predicted by theory and simulations.

2.4 NANOSTRUCTURED MAGNETIC MEMORIES

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Magnetic random-access memories

This section addresses the application of magnetic devices in future nanomagneto-electronic circuits. Present-day magnetic random-access memories (MRAMs) are based on the effect of giant magnetoresistance (GMR). An MRAM

consist in essence of an array of memory cells containing ultra-small magnetic elements. Each magnetic element is a sandwich of alternating magnetic and normal metal ultrathin films, in which the magnetic layers can have mutually parallel or anti-parallel orientations in magnetic state. The electronic effects exploited are the differences in transport properties and density of states for spin-up and spin-down electrons in a magnetic metal. The application of a magnetic field affects the magnetic orientation of the layers and this induces a substantial drop in the electrical resistance of the multilayer, up to 110% at room temperature. This effect, discovered as recently as 1988, is called giant magnetoresistance. Lord Kelvin, who discovered the effect of magnetoresistance in 1857, found that materials show a maximum change of at most 5% at room temperature.

The bits are 'set' by a magnetic field generated on-chip by two crossing conductors carrying a current. The content of a memory cell can be read by silicon sensing circuits through a measurement of the change in the cell's magnetoresistance.

The multilayers themselves are a clear example of one-dimensional nanotechnology. The thicknesses of the individual layers typically vary from 1 to 5 nm and a high uniformity is required. Most of the effort is now focused on reducing the lateral dimensions of the magnetic cells. Cell sizes with lateral dimensions as small as about one micron have been demonstrated (table 2.4.1), while some efforts are being made to approach the nanoscale limit of 100 nm [Wang, 1996; Pohm, 1994]. The structures are currently fabricated using electron-beam lithography.

Table 2.4.1

Specifications of some recent circuits demonstrated by the companies Honeywell, Non-Volatile Electronics (NVE) and INESC.

source	Honeywell (USA) [Ranmuthu, 1992]	NVE (USA) [Brown, 1994]	NVE (USA) [Pohm, 1995]	INESC (Portugal) [Melo, 1997]
storage capacity	512 kbit	4 x 256 kbit	16 Mbit	400 bit
die size (cm ²)	0.3	0.9	0.9	
bit size (μm ²)	2.8 x 10	1.4 x 6.1	1.0 x 2.2	7.6 x 3.2
readout speed (MHz)	1.42	4	5.2	
writing speed (MHz)	14.2	10		
GMR change	2%	6%	5-6%	2-5%
materials	2 x15 nm NiFeCo separated by 5 nm Ta	2 x 5 nm ternary alloys separated by 3 nm Cu		5 to 10 nm thick NiFe, Cu and Co layers

For the coming 5 to 15 years, a continuous improvement is expected in the performance of the existing circuits and cells by the introduction of new and optimized giant-magnetoresistant materials. Table 2.4.2 and 2.4.3 show 1995 estimates that the cell's critical two-dimensional lateral dimensions reach the 100-nm limit in 1998. Experimentally, 200-nm individual cells were demonstrated

to produce 8% giant magnetoresistance, with a clear memory effect. Incidentally, the first drives with heads made from giant magnetoresistive materials were shipped by IBM in January 1998 [Mathur, 1998].

Table 2.4.2

Roadmap of magnetic random-access memories (MRAM) storage. Source: US Defense Advanced Research Projects Agency (DARPA) [Patten, 1996]

year	1995	1998
speed (MHz)	3-30	> 100
power (mW)	< 10	<< 10
minimum feature size (nm)	200	100
cyclability	infinite	infinite

Table 2.4.3

Estimates of the density and performance of non-volatile sub-micron magnetic memory cells assuming a 6% giant magnetoresistance in spin-valve structures, 15 Ohm/square resistance²⁶ and a 25-MHz cycle. Source: Non-Volatile Electronics [Pohm, 1996]

cell width (nm)	cell area (μm^2)	capacity (Mbit)	die size (cm^2)
400	1.90	16	0.9
200	0.55	64	1.0
100	0.19	256	1.4

Table 2.4.4

Predictions for the storage capacity (bits) achievable on a 400 mm² chip for different minimum feature sizes λ (nm), aiming to match the speed of static random-access memory (SRAM), dynamic random-access memory (DRAM) and Flash-type non-volatile memory. Source: Honeywell [Granly, 1996]

minimum feature size λ (nm) \ Speed	SRAM (30-50 MHz)	DRAM (14-16 MHz)	Flash (7-8 MHz)
500	4 M	16 M	32 M
350	16 M	64 M	128 M
200	64 M	256 M	512 M
150	256 M	1 G	2 G
80	1 G	4 G	8 G
GMR cell size	40 λ^2	10 λ^2	8 λ^2

Nanoscale magnetoelectronic phenomena and devices

The use of memory nodes based on tunnel magnetoresistance (TMR) is a new development in the magnetic random access memories area. In brief, these components are a trilayer structure consisting of two ferromagnetic metals, spaced by a 1 to 2 nm-thick tunneling barrier (usually aluminum oxide). Microstructured magnetic tunnel-junction devices with sizes down to 125 x 250 nm² have been demonstrated at IBM using established techniques [Gallagher, 1997]. For the future implementation of the memory circuit some other requirements have to be met, of which the most demanding are control of layer thicknesses and uniformity and the control of magnetic field required to switch the cells. It is clear, however, that magnetic cells with nanoscale dimensions are possible and that memory-cell sizes in circuits are determined by the scaling laws for complementary metal-oxide semiconductor (CMOS) integrated circuits. Another new line of research is the development of materials such as magnetic

²⁶ A unit used in microelectronics to characterize lateral structures with a fixed film thickness.

oxides that show colossal magnetoresistance (CMR). This effect, discovered in 1994, is the occurrence of a 10,000 fold reduction of the electric resistance found in perovskites, a class of compound materials that also includes high-temperature superconductors. The usefulness of colossal-magnetoresistance effects is still limited because they occur at low temperatures and, in general, at much higher fields. Also, nanoscale studies have not been reported so far. Still, the strong response of colossal-magnetoresistance effects to magnetic fields should make them good sensors for use, for example, in computer disk drives based on magnetoresistance. And finally, quantized magnetic disks based on the magnetic force microscope (MFM) are also under development (section 2.2.4).

Experiments on giant, tunnel, and colossal magnetoresistance in nanoscale structures are continuously being reported. For integration into devices, control of the magnetic properties of nanoscale magnetic contacts and nanowires is essential. Much has to be learned about their characteristics, such as the control of the magnetic switching behavior and various other micromagnetic issues. One field of research concerns the fabrication of magnetic nanowires to study the relation between the magnetic switching field and the width of the wire. Also, many experiments are presently set up to study the properties of nanosized magnetic particles (section 3.2.3). On the nanoscale, magnetic materials start to behave differently. Some of the material properties must therefore be investigated to assess the limits of nanomagnetoelectronics. When the size of a magnetic particle is decreased below some critical value (10 nm for cobalt), the superparamagnetic effect sets in at room temperature. Below that size, the thermal activation is strong enough to overcome the ferromagnetic ordering in the structure and the ferromagnetic behavior is lost. As a result, these nanoscale magnetic bits lose their magnetic orientation and hence information at room temperature fields on, for instance, a hard disk. However, hard disk drive manufacturers are nearly a decade away from encountering the superparamagnetic effect and will probably invent other technologies to counter this effect [Boyer, 1997].

Novel device structures and materials offer new perspectives on magnetoelectronics. One example is the combination of magnetic nanostructures and semiconductors in a single component, in which spin-dependent transport can possibly be exploited. In such components, the most important feature of the electrical current is its degree of magnetic polarization. A spin-polarized current can be injected into a semiconductor (or another conducting channel) from a single-domain ferromagnetic contact. The degree of spin-polarization can be modulated in various ways and detected in a second magnetic contact. Such spin-dependent transport phenomena occur when the device dimensions are on the order of the spin-diffusion length, which is typically on the order of 100 nm at room temperature. In other device structures, ballistic carrier transport will

be used (carrier transport with conservation of momentum). When hot electron transport in magnetic multilayers is understood and controlled it may lead to a new class of magnetoelectronic nanoscale devices.

Spin-tunneling effects are being demonstrated in multilayers comprising these oxide materials. Yet another class of materials with intriguing optical, magnetic and electronic properties are dilute magnetic semiconductors. Quantum-confinement phenomena, already known for regular semiconductor heterostructures, are beginning to be explored in these materials. Further, single-electron effects in ferromagnetic particles are being considered to investigate the potential of magnetically controlled Coulomb blockade effects. For the fabrication of the nanoscale magnetic islands needed in a Coulomb blockade device, self-assembly techniques such as phase separation in an oversaturated material are an excellent alternative to more standard processing techniques.

Architecture

It is clear that magnetic devices have no difficulty following the scaling laws of the silicon industry. So far, the demonstrations of nanoscale magnetic memory and logic circuits use conventional architectures: magnetic random-access memories (MRAM) circuits adopt the architecture of dynamic random-access memories (DRAMs) based on CMOS. When the limits of silicon nanoelectronics are reached, magnetic devices can continue to play an important role in increasing the functionality of the components and circuits, both memory and logic. In the future, the application of nanoscale magnetic devices may help to realize completely different computing concepts. When new architectures for computing, such as quantum cellular automata and quantum computing, mature new opportunities arise for spin-based electronics using nanostructured elements.

Conclusions

Present-day magnetic random-access memories are based on giant magnetoresistance. This storage technology looks as if it will run out of tricks around 2010 [The Economist, 1997]. The further miniaturization of magnetic data storage might depend on nanoscale phenomena such as quantum confinement and the superparamagnetic effect, that trigger the quest for device concepts based on novel principles. Scientist are only just beginning to understand the potential of such new concepts [Chou, 1997]. There is a strong need for high-risk research to assess the potential for magnetoelectronic devices based on phenomena beyond giant magnetoresistance.

2.5 QUANTUM PHENOMENA IN NANOSCALE STRUCTURES

P. Hadley²⁷

Introduction

A. ten Wolde

One fascinating aspect of nanotechnology is that nanostructures can be made that behave quantum-mechanically. Quantum mechanics is the set of laws of physics describing the motion of subatomic particles such as electrons, protons, and neutrons. The word quantum was introduced to describe how at this level, energy is exchanged in discrete packages. In particular, atoms absorb and emit light in the form of photons, which are particle-like packages with an energy $h\nu$, where h is Planck's constant and ν the optical frequency. Quantum mechanics tells us that electrons swarm around the nucleus of an atom in an electron cloud, with wave-like properties, that has a typical diameter of a few tenths of a nanometer. The wave-like behavior of particles is an essential feature of quantum mechanics, and causes particles to behave differently than one would expect on basis of the laws of classical mechanics that rule our everyday lives. For instance, Heisenberg's uncertainty principle tells us that it is fundamentally impossible to determine the position and the velocity of a subatomic particle with a high accuracy: that particles have an intrinsic 'fuzziness'. One of the most striking quantum phenomena is tunneling. A particle, for instance an electron, can cross a potential energy barrier even though classically, it doesn't have enough energy for this. Quantum mechanics allows this because the electron's extended wavefunction has a small, but finite value on the other side of the barrier. Various new electronic devices are based on tunneling.

Another important phenomenon is quantum confinement (section 2.3), inducing (a change in the) resonant states with discrete energy bands or levels. This provides a major opportunity for materials science and engineering, because various 'fundamental' macroscopic properties (electronic, optical, electrical, magnetic, chemical, and mechanical) prove 'tunable' by introducing quantum confinement in nanostructured materials (section 3.1). Insofar as it is possible to change as well as detect the quantized states of individual particles (for instance, spin up or down), the energy levels can also be used to store information. The quantum-mechanical effect of superparamagnetism was already mentioned (section 2.4).

Finally, waves have a phase. With a thin enough barrier between two superconductors, the phase of the electron wavefunction at one side of a junction can maintain a fixed relationship with the phase of the wavefunction on the other side. This linking of phase is called phase coherence, and is the essence of the Josephson effect. One of the characteristics of a Josephson junction (a quantum

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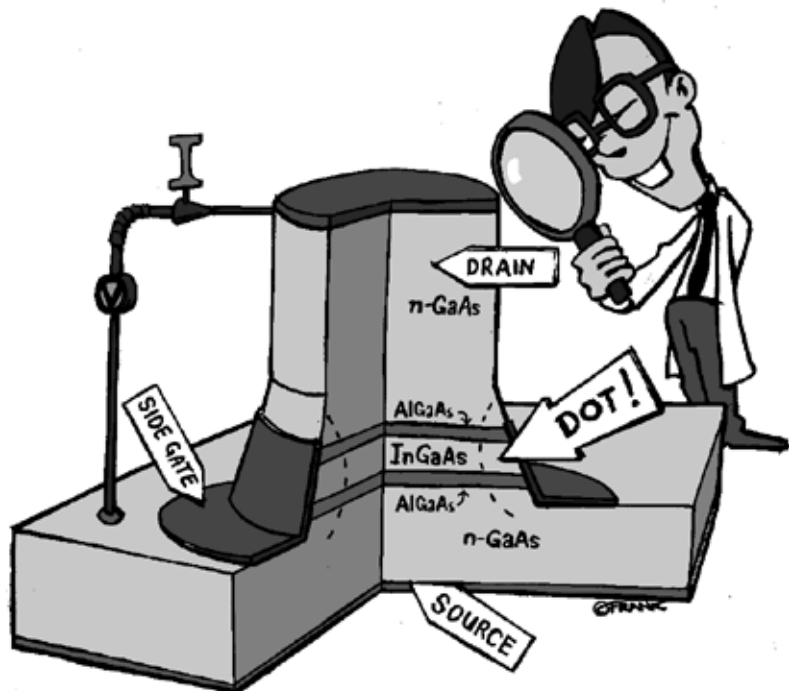
device developed in the nineteen eighties) is that as the temperature is lowered, superconducting current flows through it even in the absence of voltage difference between the electrodes.

The reign of quantum physics extends from the subatomic to the nanoscale. Since this determines some of the properties of nanostructures, understanding these phenomena is highly relevant to eventually controlling them and using them to our advantage.

Artificial atoms

Instead of trying to measure the quantum-mechanical behavior of single atoms directly, one can also create artificial atoms. As discussed in section 2.3, nanotechnology can be used to construct quantum dots. In such a nanosized structure, the electron becomes confined within the geometric dimensions of the dot, leading to localization. The resulting electronic states can be compared those inside an atom, where the electron is confined to by the attractive Coulomb potential. Hence these quantum dots are called artificial atoms, even though they have sizes much bigger than ordinary ones. They are interesting both for scientific reasons and possible applications. Figure 2.5.1 shows a vertical quantum dot (electron transport through the disk-shaped dot is in the vertical direction). The disk can contain one, two or more electrons. Figure 2.5.2 shows an electrical measurement from which it can be determined that the electrons behave as if they were part of a 'pancake' atom. Every time an electron is

Figure 2.5.1
Schematic drawing of a vertical quantum dot fabricated at the Nippon Telegraph and Telephone Corporation (NTT) in Japan. The electrons in this semiconducting structure are trapped in a thin disk at the position labeled 'dot' between two tunnel barriers. Source: [van der Zant, 1997], after [Tarucha, 1996]



added to the dot, a new artificial atomic element is created: from the equivalent of hydrogen to helium, lithium etc. By calculating the ionization energy of each artificial atom from the measurement, a whole new periodic table can be determined in this single device (figure 2.5.3). The table shows that like three-dimensional atoms, these ‘pancake’ atoms have a shell structure. This means that the electrons pair up according to spin selection rules, but that the shell structure is different.

Figure 2.5.2

The measured current through the quantum dot from figure 2.5.1 as a function of the gate voltage and the bias voltage. When the voltage is increased above certain thresholds, an extra electron enters the quantum dot. The size of the black diamonds determines the amount of energy that is necessary to add this electron, which is the equivalent of the ionization energy for this artificial ‘pancake’ atom. Reprinted with permission from [Kouwenhoven, 1997]. Copyright 1997 American Association for the Advancement of Science. For a color print of this figure see page 310.

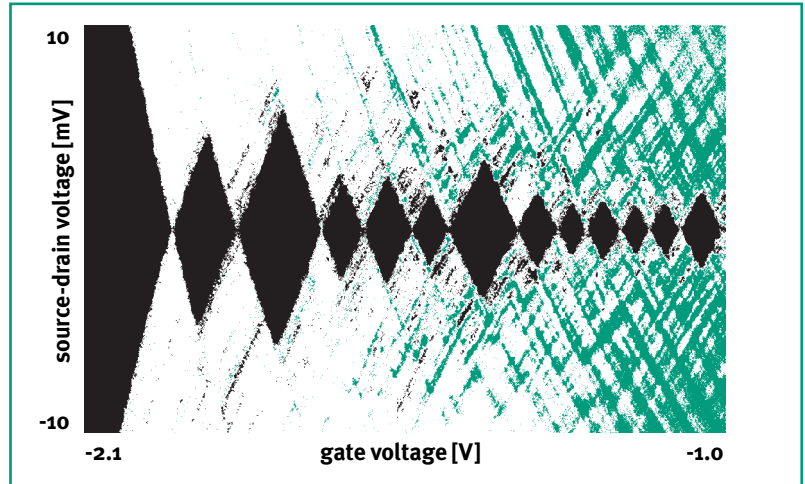
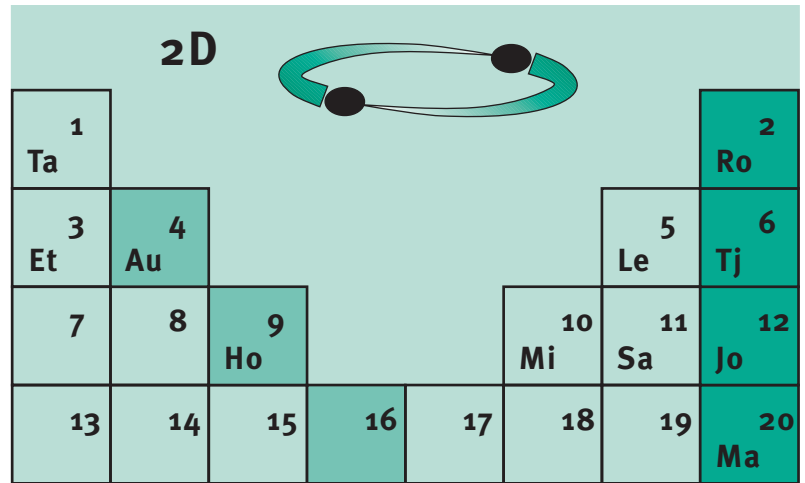


Figure 2.5.3

Just for fun: the periodic table of ‘pancake’ artificial atoms. The names of the elements have been derived from the names of the researchers. Source: [van der Zant, 1997]



Artificial atoms have properties that can be very different from those of real atoms. For instance, it is possible to couple a thousand times more magnetic flux to an artificial atom than to real atoms, simply because the artificial atoms are bigger. This enables the study of magnetically induced atomic states that are inaccessible in the realm of real atoms. Artificial atoms can be manipulated by electric and magnetic fields in ways not possible with real atoms. Having new

atoms with properties that can be tuned could have many applications. Many of the experiments carried out on artificial atoms have been performed at low temperatures. This is because the energy separation of real or artificial atoms depend on the size of the structure. These spacings have to be larger than the energies of thermal fluctuations in order for the atomic structure to be observable. In real atoms the energy spacing between quantum levels is typically several orders of magnitude larger than the thermal fluctuation energy at room temperature; thus quantized energy levels of real atoms are easily distinguished. In contrast, most of the artificial atoms that have been made so far are relatively large and the temperature at which their atomic structure becomes apparent is rather low. As advances in nanotechnology continue, the size of the structures will decrease and the temperatures at which the atomic structures will be observable will increase correspondingly. This will open the way to room-temperature applications; the room-temperature device mentioned in section 2.2.4 cannot yet be applied due to its impedance.

One of the possible applications of artificial atoms is a nanoscale quantum computer. Quantum computing makes use of coherent states to process information. Rather than the sequential discrete logic of conventional information processing, use is made of quantum superposition of so-called qubits. Quantum computers, if they could be built, would be able to perform certain complicated tasks faster than conventional computers. For the realization of quantum computers the emphasis has so far been on quantum optics, using trapped atoms or ions. Nanotechnology could make solid-state quantum devices for quantum computing possible.

Artificial molecules

One of the most exciting areas of research is the possibility of coupling artificial atoms to form artificial molecules. Just as quantum films can be used to tailor a multilayer stack with special properties and quantum wires can be used to tailor a film, quantum dots can be used to tailor wires, films and superlattices by placing them in some (regular) pattern. Scientists are just beginning to explore these possibilities. The main obstacle is that the growth techniques for producing quantum dots discussed in section 2.3 are inherently random, leading to uncontrollable variations in shape and size. However, modified growth schemes with increased control have already produced artificial molecules [Schedelbeck, 1997]. As an alternative, scanning probe fabrication has been used to synthesize, for example, previously non-existing salt molecules, but this is still an emerging technology as well.

A number of predictions have been made for the electrical conductivity in such systems. Normally, electrical conduction is governed by the motion of electrons that flow like a liquid through a conducting material. As the electron liquid is cooled, it can condense into a number of different quantized states. This can

induce superconductive or magnetic behavior, one-dimensional flow (Luttinger liquids), charge density waves, spin density waves, or the formation of Wigner crystals. The type of condensed state that is observed depends on the electron-electron interactions in the given material. The effects of these interactions are intensified in (quasi-)one dimensional conductors such as molecular wires and single rows of atoms on a substrate. The interactions are more important in one-dimensional conductors because the diameter of the wire is smaller than the effective radius of the conduction electrons. In that case, the electrons cannot pass by each other and the motion of the electrons is determined by the interactions. Using nanofabrication it is possible to fabricate one-dimensional wires by a number of different means. Atoms can be deposited in a row, or atoms can be pushed into a row with a scanning tunneling microscope, or individual long conducting molecules can be attached to the electrodes. The enhanced electron-electron interactions in these structures and the condensed states they produce can then be explored by cooling the atomic wires down. Work is continuing towards fabricating such quantum wires.

Measuring quantum phenomena

As explained in section 2.3, nanofabrication can be used to create a large variety of structures that exhibit quantum effects. One of the difficulties in coupling the macroscopic world to the microscopic world is bringing probes close enough to a nanostructure to be able to measure it. Scanning tunneling microscopes do of course offer many possibilities. The quantum corrals in figure 2.2.19 and also in figure 5.2.4 show how the electron clouds of the copper surface electrons have been modified by the addition of the iron atoms. The interference patterns visible are a manifestation of the wave nature of electrons. Probing electron clouds can also be used to study atomic interactions. For instance, figure 2.5.4 shows a silicon atom at a surface. Due to the interaction with the lattice and the conduction electrons there is an electron cloud around the silicon atom with a diameter of several nanometers. This cloud, showing up

Figure 2.5.4

Scanning tunneling microscope image of the electron cloud around a single silicon atom that is embedded in the atomic lattice of a semiconducting crystal of gallium arsenide (fine stripes). The diameter of the electron cloud (bump and ring) stretches up to ten nanometers. This type of electron cloud is called a Friedel oscillation. Reprinted with permission from [van der Wielen, 1996]. Copyright 1996 by the American Physical Society.



as a bump and a ring, is sensitive to surrounding potentials. For example, the electron cloud of the silicon atom can be deformed in a controlled way by applying a voltage to an electrode close to the atom. This sort of interaction between the macroscopic world of electrical contacts and microscopic world of atoms is an important aspect of science at the nanometer scale.

Figure 2.5.5

Scanning electron microscope (SEM) image of a 20-nm palladium particle (yellow) that has been electrostatically trapped between two electrodes. Reprinted with permission from [Bezryadin, 1997]. Copyright 1997 American Institute of Physics and American Vacuum Society.

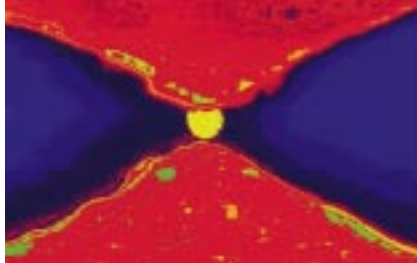
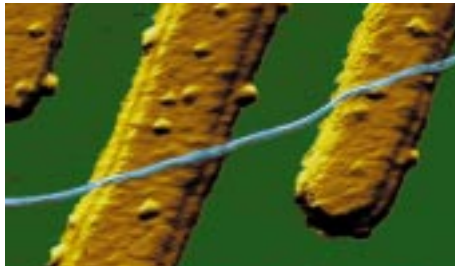


Figure 2.5.6

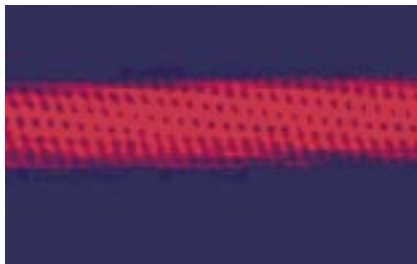
Atomic-force image of an individual single-wall carbon nanotube about 1 nm in diameter, connected to two 15-nm-thick electrical leads for electrical measurements. The total length of the tube is 3 μm , with a section 140-nm long between the contacts. The device was made as part of a collaboration between the DIMES institute at Delft University and Richard E. Smalley. Reprinted with permission from Nature [Tans, 1997]. Copyright 1997 Macmillan Magazines Limited.



However, precisely these difficulties in achieving electrical contact have so far prevented scanning probes from measuring the electrical properties of individual nanostructures. Figures 2.5.5 and 2.5.6 show how a small metallic cluster and a carbon nanotube have been coupled to electrical leads for this purpose. The nanotube is only a few atoms thick. The tube proved to conduct electricity as easily as if it were a metal, which makes it an interesting candidate for connecting future nanoelectronic components. A close-up image of a carbon nanotube is shown in figure 2.5.7. The precise conducting properties – metallic or semiconducting – of the tube depend on the diameter of the tube and on the twist of the atomic arrangement [Wildöer, 1998; Odom; 1998].

Figure 2.5.7

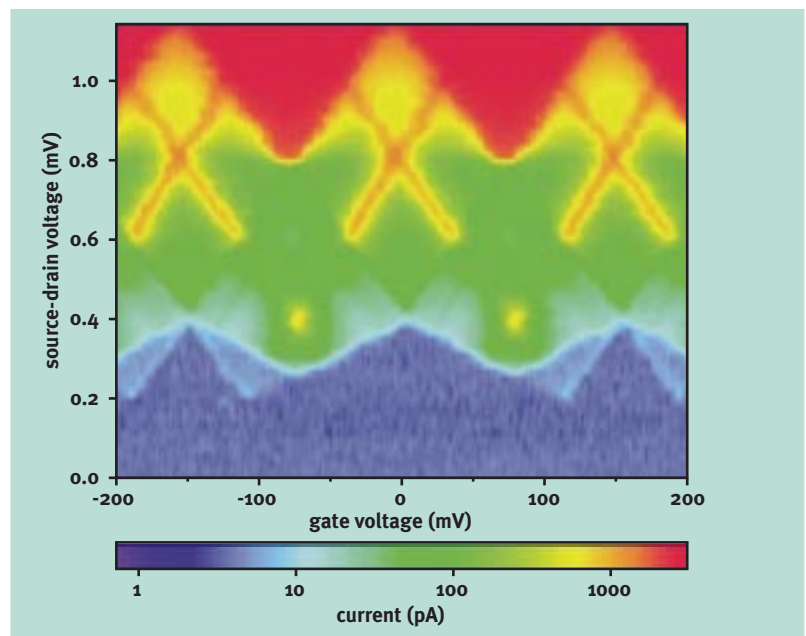
Atomic resolution scanning tunneling microscope (STM) image of a carbon nanotube. The diameter of the tube and the twist of the atomic arrangement along the tube determines the electrical conductivity of the tube. Reprinted with permission from Nature [Wildöer, 1998]. Copyright 1998 Macmillan Magazines Limited.



Another example of a quantum effect in a nanostructure is the single-electron charging effect: the current through a very small structure shows a periodic rise and fall each time another electron tunnels onto this structure. This effect arises due to the finite energy that is needed to charge very small structures with a single electron. It can be used to monitor and manipulate individual electrons. Charging effects can be used to build a single electron tunneling (SET) transistor (section 2.2.4). These transistors can be used for logic and memory circuits. Unlike conventional semiconductor transistors, single-electron tunneling transistors can be scaled down to atomic dimensions. The current that flows through a superconducting single-electron tunneling transistor is shown in figure 2.5.8. There are many other quantum effects occurring in nanostructures. For instance, details of the quantum Hall state were recently probed using scanning probe microscopy [Levi, 1998a]. The quantum Hall effect, discovered in 1980, is the occurrence of a stepwise increase in the (quantized) conductance for quantum wells at very low temperature and high magnetic fields. Recently, the Kondo phenomenon was observed in a quantum dot; this is a truly many-body effect requiring coherent overlap between the localized electrons in the dot and a continuum of electron states outside the dot [Levi, 1998b]. And finally, experiments by Delft scientists recently revealed that both the magnetic and the electrostatic Aharonov-Bohm effect can occur in micrometer-sized metal rings with $60 \times 60 \text{ nm}^2$ junctions [van Oudenaarden, 1998]. The Aharonov-Bohm effect, predicted in 1959, occurs because the quantum-mechanical phase of the electron wavefunction can be changed by electromagnetic potentials, and showed up as oscillations in the conductivity.

Figure 2.5.8

Single-electron charging effect: the current through a superconducting single-electron tunneling (SET) transistor. The pattern repeats itself horizontally each time the gate voltage pulls another electron tunnels onto the central island. Blue = nearly no current, red = high current.



2.6 NOVEL DESIGNS

A. *ten Wolde*

The future of computing is a hot topic. Not only do computers increasingly influence our daily lives, they also represent tremendous commercial interests. According to figures from Dataquest and VLSI Research in January 1998, semiconductor sales during 1997 amounted to \$152 billion, and are expected to rise to \$331 billion in 2002. The sales of equipment for semiconductor chip manufacturing, such as wafer steppers, is estimated at \$22 million (1997) and \$42 million (2002). For the scientific audience, Elsevier has published a good overview of the current status and future of electronic devices [Vettiger, 1996]. A fascinating vision on future computers for a more general audience with a technical background, 'Technologies and designs for electronic nanocomputers', has been compiled by the American MITRE organization in McLean, Virginia [Montemerlo, 1996]. After recognizing that nanocomputers based on other operating principles (mechanical, chemical, or quantum logic) may ultimately prove superior, their report focuses on devices and computers based on nanostructured electronic components. The main reason for this choice is that in the near future, at least, electronic nanocomputers are most likely to use the fifty years of experience with larger electronic computers.

Proposed nanoelectronic components

The heart of a microcomputer is the *metal-oxide-semiconductor field effect transistor (MOSFET)*. Basically, it allows one to switch an electric current between two electrodes called the 'source' and 'drain' between 'on' and 'off' by changing the voltage on the 'gate' electrode. One of the possible routes to nanoelectronics is miniaturizing the MOSFET down to the nanoscale. Several obstacles are expected, including high electric fields, tunneling of electrons, local heat, and the replacement of crucial bulk properties with quantum behavior. In particular, semiconductance as induced by random impurity doping is a bulk property that vanishes at the nanoscale because even the highest concentrations of dopant atoms are extremely dilute from an atomic point of view. Still, scientists have recently produced functioning 10-nm long MOSFETs [Guo, 1997]. Theoretical considerations show that the obstacle of vanishing bulk properties is non-existent: when the length of the channel between source and drain becomes small enough, doping of the channel material becomes unnecessary because charge carriers may be delivered by the contacts [Pikus, 1997; Tucker, 1998]. Building ultra-large-scale integrated circuits (ULSIs) from these nanosized MOSFETs requires additional breakthroughs, especially in patterning technologies such as scanning probe lithography [Asai, 1996]. Still, it is expected that the down-scaling of MOSFETs can continue to at least 50 nm and maybe even 10 nm [Hillenius, 1997; Ahmed, 1997].

The downscaling of the MOSFET and other microelectronic devices based on classical electronic effects to nanometer dimensions will turn silicon technology into a nanotechnology in the very near future. However, this miniaturization is not aimed at adding new functionalities based on nanoscale phenomena, such as quantum effects. Rather, the occurrence of such effects as a consequence of shrinkage to nanoscale dimensions is viewed as a nuisance. It is clear that this approach will break down at a certain point. When the sample size becomes on the order of the electron wavelength, fundamental quantum-mechanical properties will start to dominate the electrical performance. For instance, faster and faster switching operations will introduce an increasing uncertainty in the energetic change involved. If the uncertainty becomes as large as the energy step itself, the switching event becomes unreliable [Geerligs, 1997]. In nanoscale field-effect transistors, the transport of charge between source and drain should be viewed in terms of the transfer of individual electrons rather than in terms of a continuous electrical current. So instead of downscaling microelectronic devices, it has also been proposed to develop novel devices that are inherently based on quantum effects.

For this purpose, novel semiconducting, metallic and superconducting mesoscopic structures (or combinations of such structures) with new length and energy scales have been developed in recent years.

Quantum dots (section 2.3) form the basis of various novel devices discussed below, and could also form the basis for nanostructured magnetic memories (section 2.2.3). Electrostatic *quantum dot cellular automata (QCA)* have been proposed as the basis for a radically different type of electronic circuit (figure 2.6.3).

In the laboratory, *resonant tunneling devices (RTDs)* have been developed that can switch a current through a tunneling barrier (figure 2.6.1). Their application might be sped up by integrating them in conventional microelectronic devices to form resonant tunneling transistors. In fact, scientists at Texas Instruments²⁸ demonstrated the first quantum integrated circuit that operates at room temperature using a combination of resonant tunneling transistors and conventional bipolar transistors in 1993. The technology for mass scale fabrication of such hybrid transistors already exists [Montemerlo, 1996].

Another nanoelectronic device based on quantum tunneling is the *single electron tunneling (SET)* device (figure 2.6.2). In the laboratory, continued miniaturization of these devices is increasing their temperature of operation from cryogenic to room temperature: room-temperature operation has in fact been observed but is still unreliable [The Economist, 1998]. A single electron tunneling *transistor* may be viewed as a quantum dot that is weakly coupled to the source and drain electrodes via tunneling barriers [Kastner, 1993]. The charge and energy of the electrons in the dot are quantized, very similar to the electrons in an atom. The energy corresponding to the removal from or the addition

²⁸ <http://www.ti.com/corp/docs/history/quantumic.htm>

to the dot of a single electron is then also quantized, resulting in a ‘Coulomb staircase’ in the current-voltage characteristics of these devices [Kouwenhoven, 1995]. Two types of single electron tunneling devices have been prepared so far: a first type relies on the use of doped semiconducting dots which contain only very few electrons; a second type relies on the use of metallic dots defined in thin metal films. The latter example shows that nanoelectronics is not necessarily based on silicon devices. A single electron *memory* element has also been fabricated [Ahmed, 1996b].

Finally, a 10-THz compound semiconductor transistor was recently proposed that is based on plasma-waves rather than electronic conduction [Marks, 1998].

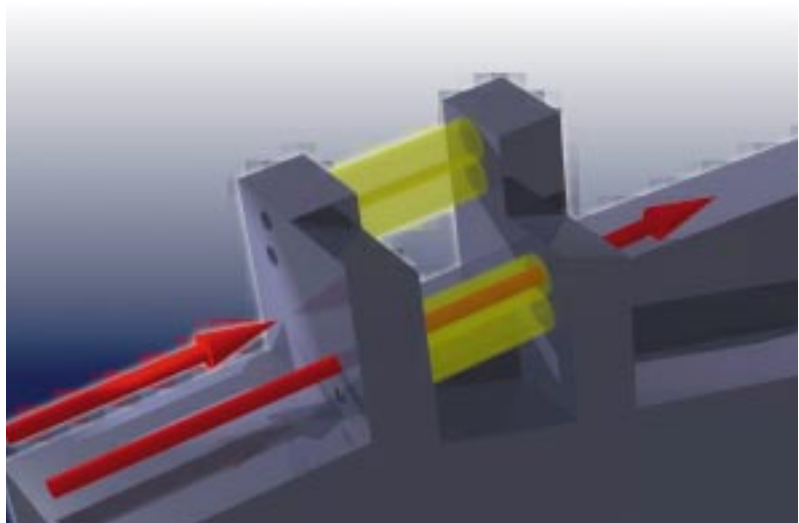
Proposed components for molecular electronics

When downscaling further and further, eventually one ends up working with molecules. Scientists have already produced *molecular switches* consisting of several molecules (figure 4.2.6). Transistors using self-assembling monolayers of organic molecules as a dielectric are discussed in section 4.8. Charge transport has been directly observed through single molecules that were self-assembled onto the two facing gold electrodes of a mechanically controllable break junction. The effect of different molecular alligator clips on the molecule-scale wire’s conductivity is being investigated [Reinerth, 1997]. Metal-containing polymers with a temperature-induced spin transition have been proposed as *high-density storage devices* with a 4-nm bit size [Kahn, 1998].

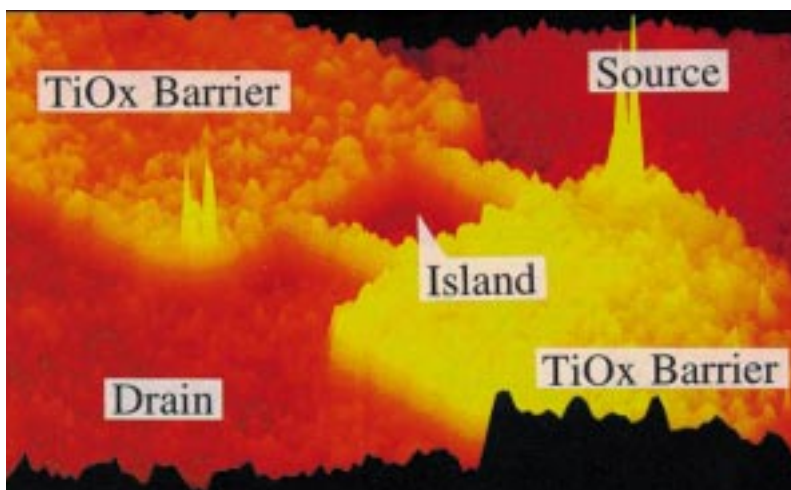
The wiring of nanoscale components can be achieved with *molecular wires*. Besides being electrically conducting (metallic) and structurally rigid they must also be synthesized in a controlled way with respect to length and molecular structure (insofar this influences the conducting properties). Much research is being carried out on conducting polymers and some on conducting proteins

Figure 2.6.1

Artist’s impression of the working principle of a resonant tunneling device (RTD). The figure shows the potential energy diagram. Electrons move towards the location with lowest potential energy under the influence of the electric fields. In the situation on the left, they cannot penetrate the barrier presented by the potential energy well. In the situation on the right the quantized energy levels in the well have been lowered by applying a voltage across the device (‘downhill slope’) so that one of the levels coincides with the energy of the electrons. The electrons pass through the barrier through quantum tunneling and a current flows through the device. Adapted from [Montemerlo, 1996]



a



b

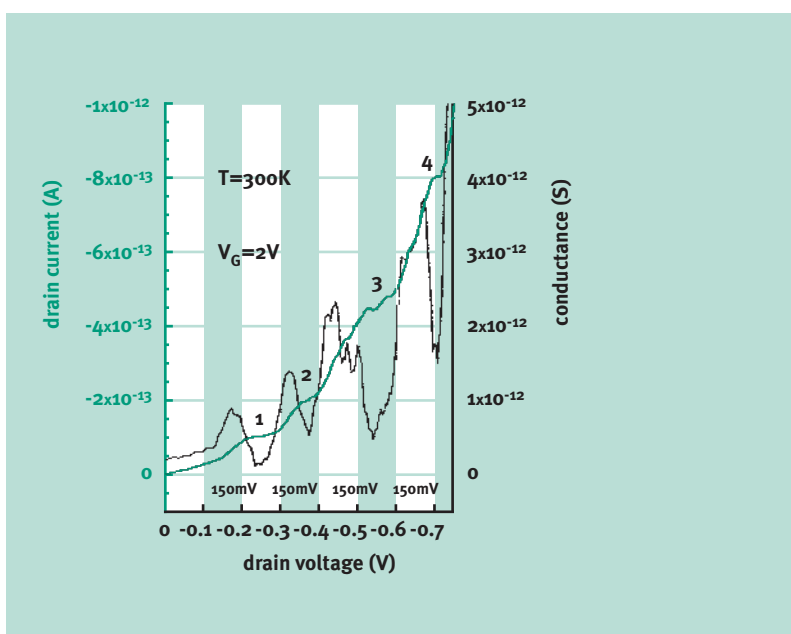


Figure 2.6.2

Single-electron tunneling (SET) device operating at room temperature, fabricated with a scanning probe according to figure 2.2.26.

(a) Atomic-force microscope picture showing source and drain made from oxidized titanium (light) surrounding a metallic titanium island of about $30 \times 30 \text{ nm}^2$ (dark). The island is so small that it can only hold a few free electrons. Extra electrons are prevented from entering the island by the electrostatic repulsion from those already occupying the island, a phenomenon called the Coulomb blockade. A voltage applied to the gate below the surface diminishes the blockade so that one electron at a time can flow through the island, leading to a measurable current. If the voltage is increased further, the extra electron is allowed to stay on the island and the current stops. A further increase induces the flow of yet another electron, etc.

(b) Varying the drain voltage of the device for a fixed gate bias of 2 V leads to the observation of the so-called ‘Coulomb staircase’, a characteristic stepwise increase in the drain current that is accompanied by peaks in the conductance. See also figure 2.5.8. Reprinted with permission from [Matsumoto, 1996].

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Figure 2.6.3

Artist's impression of a quantum dot cellular automata (QCA) circuit functioning as a 'majority gate': the output value equals the value of the majority of the input values. Each quantum dot cell of this theoretical component consists of five dots and contains two electrons that can move within the cell. Due to their mutual repulsion, they quickly locate themselves on two of the dots at opposite corners of the cell. Since there are four corners, each cell can assume two states ('1' and '0'). The cells communicate by the electric fields of their electrons. They are in such close contact that the alteration of the value of one cell induces a domino-like effect in all the other ones. There is no flow of current. A fundamental problem that is still a subject of investigation is the occurrence of logical conflicts, caused by back propagation of the signal. Adapted from [Montemerlo, 1996]

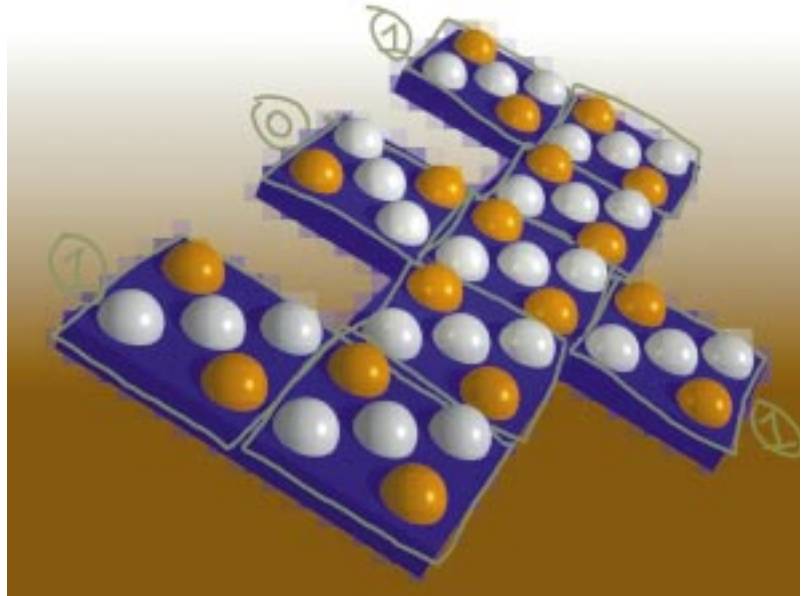
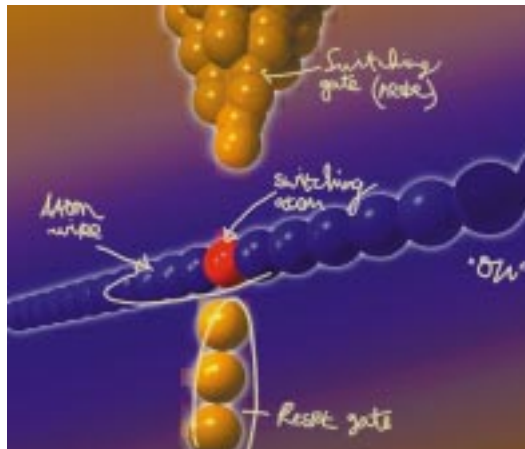
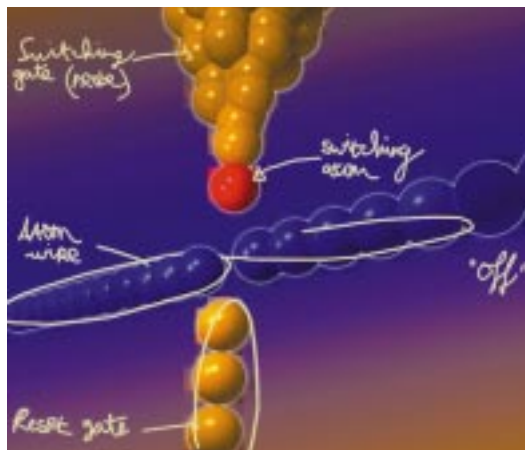


Figure 2.6.4

Artist's impression of an atom relay transistor (ART). (a) When the switching atom is part of the horizontal wire of atoms, the wire conducts a current and the signal is 'on'. (b) By applying a force with the reset gate, the atom is pushed out of the wire and the current stops ('off'). After [Wada, 1997]



a



b

[Nicolini, 1995]. Metallic carbon nanotubes, also called buckytubes, are another popular candidate for molecular wires [Tans, 1997].

Because buckytubes can behave as semiconductors as well, they can also function as a *molecular diode* (figure 4.10.2) and, as was demonstrated very recently by Dutch scientists, even as a *molecular transistor* [Tans, 1998]. The current through a nanowire between two electrodes – acting as source and drain – could be regulated at room temperature by the voltage on a third electrode (the gate). The first successful synthesis of a molecule that could act as a transistor was announced earlier [Reinerth, 1997]. It consists of three arms that function as source, drain and gate. The molecule is in an excited, polarized state called a polaron. It is the polarons that move through the material, not the electrons (section 4.8). The propagating signal can be envisaged as electron clouds influencing each other in a domino-like fashion. This group of researchers with others at MITRE hope to construct an adder out these molecular transistors before the year 2000.

Scientists at Hitachi have proposed a *molecular single electron switching transistor* (MOSES, a molecular SET) consisting of a polymer molecule with a conducting part acting as a quantum dot (the island) and insulating parts acting as tunnel junctions to the electrodes. The ultimate speed of this theoretical device is estimated at 10 THz [Wada, 1997]. They have also proposed and successfully simulated an *atom relay transistor* (ART) [Wada, 1993 and 1997] (figure 2.6.4). A bistable switch of atomic dimensions with a closely related design has been demonstrated experimentally: a xenon atom was reversibly transferred back and forth between the tip of a scanning probe microscope and a conducting substrate [Eigler, 1991].

The size of these elements indicates the limit of miniaturization. Larger densities for memory or processing elements consisting of atoms are physically impossible. The same is true for (linear) processing speeds. They will never surpass the – astounding – limit of 10 Pbits/s (P = peta = 10^{15}) because even the fastest electronic events at the atomic scale take time: an electron needs 0.15 femtoseconds ($1.5 \cdot 10^{-16}$ s) to orbit the hydrogen atom. Proposals for subatomic computing have not yet been reported!

Despite recent progress proving the feasibility of molecular devices, the molecular computer is still far away (section 4.15). Some scientists expect that rather than a giant leap from silicon-based computing to molecular computers, there will be an intermediate stage with hybrid technologies that combine silicon with molecular wires and devices. The first use for molecular wires might be as interconnects between conventional microelectronic devices [Ball, 1997].

Novel computers

Undoubtedly, many more fancy and fascinating schemes for nanoscale electronics will be proposed and demonstrated, perhaps even including networks of biological neural cells [Kawana, 1996]. Whether these schemes will actually be used for nanoelectronic devices going to the consumer markets is another matter. Error-tolerant architectures must be developed and applied to these quantum structures in order to achieve acceptable error rates. Device structures must be made reliable and repeatable to enable manufacturability.

Also, downscaling the size of the devices on a chip is by no means everything. The power of a computer is increasingly determined by other factors. Even the clock frequency no longer determines the speed at which it performs an actual task. Other issues such as the connection and packaging of devices on the chip, power and heat dissipation, processor design and programming determine the final characteristics and will require more attention. Room-temperature operation is also essential: although Josephson junctions have been around since the nineteen eighties, after initial high expectations, the demand for low-temperature operation has limited their use mainly to the measuring of voltages and magnetic fields, for instance using superconducting quantum interference devices (SQUIDS).

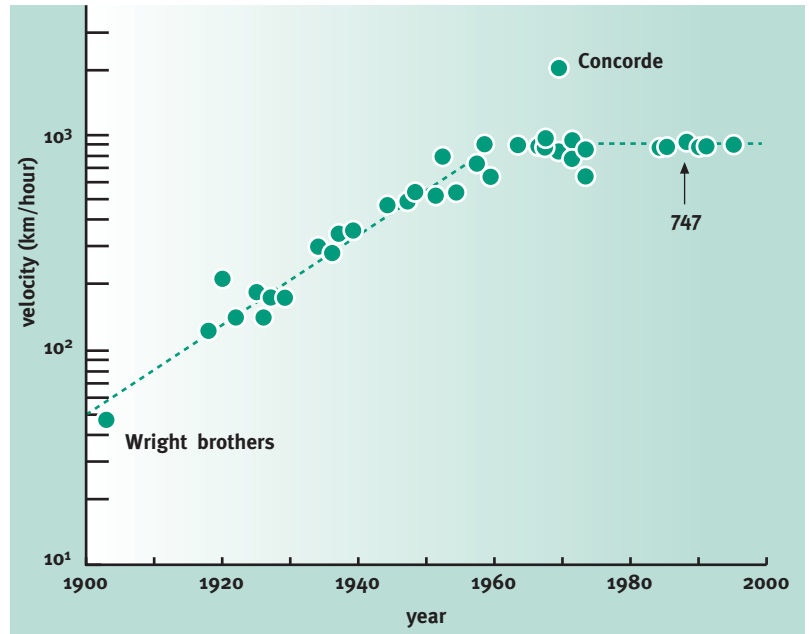
Overall, the semiconductor industry is becoming system- rather than component-oriented. It is illustrative that one of the main technical breakthroughs of 1997 was the invention of two methods (by IBM and Texas Instruments) that allow the use of copper for wiring. Using copper instead of aluminum drops the resistance delays by about 30%, which allowed the chip to operate at speeds up to 500 MHz. Superconductive wiring materials at room-temperature would be major breakthrough. Another trend is the introduction of multivalued logic, which can be implemented either classically (by distinguishing more than two voltage levels) or quantum mechanically (by distinguishing between various discrete energy levels). In fact, one of the reasons to consider the implementation of radically new nanoelectronic devices, is that they may relax the system design concepts used in conventional semiconductor technology. For instance, in order to circumvent the problem of wiring nanoscale components into a complicated electronic circuits, nanometer-scale nonlinear networks (NNNs) are considered. Such a network can 'wire itself' after receiving proper 'training'. For instance, using a simulation program, it has been shown that a neural network with periodic single electron transistor neurons and synapses can learn the logical XOR (exclusive OR) function, producing a logic 1 output if its two inputs are different and a logic 0 if the inputs are the same [Goossens, 1997].

The end of miniaturization

Eventually, miniaturization will come to an end (period 3 in figure 2.2.1). This means that somewhere around 2030, the electronics industry is expected to enter a phase of stabilization. This situation can be compared with the aviation industry during the nineteen seventies, when the increase in cruise speed of passenger air planes suddenly came to a halt (figure 2.6.5). This phase of technological maturity is not necessarily lasting; a new technological breakthrough (space flight?) can always lead to a renewed period of rapid innovation.

Figure 2.6.5

Exponential development and saturation in the aviation industry; shown is the cruise speed of new types of passenger air planes. Reprinted with permission from [Schmitz, 1997]. Copyright 1997 Nederlands Tijdschrift voor Natuurkunde.



2.7 OUTLOOK

*G. Borghs*²⁹

The field of silicon microelectronics has progressed over the last 40 years at an unmatched exponential pace in both performance and productivity. Silicon processor chips with feature sizes below 100 nm are planned before the year 2006. The promise of new computer functionalities such as speech recognition and increased artificial intelligence will continue to push the limits for processing speed and storage capacity for the decades to come.

Making things smaller reduces the cost per function, and a larger number of functions in a smaller area increases performance. Optimists believe the present trend will continue for at least the next ten years. However, pessimistic views foresee enormous difficulties on several levels when dimensions become smaller than 100 nm and predict Moore's laws will no longer be valid. Even when technical problems might be overcome, further shrinking dimensions may become prohibitively expensive. The industry is currently busy choosing from the technical options for manufacturing the first generation of nanoelectronic devices. Concrete recommendations regarding this issue cannot be given at this stage.

In conventional silicon technology, the occurrence of nanoscale effects as a consequence of continued miniaturization is viewed as a nuisance. In contrast, future-oriented research aims at the development of novel electronic devices that are inherently based on nanoscale phenomena such as quantum tunneling and discrete spin states. A long-term research strategy and funding is necessary to turn these concepts into technologies.

In spite of the cost reduction per function, costs form an obstacle for the development of nanoelectronics. The switch to a new lithographic technology for manufacturing requires extra investments from the industry, while the added value of further miniaturization in itself is decreasing. It is hoped that bottom-up techniques such as chemical self-assembly will help to reduce the costs of nanostructuring.

The situation for computer memories is slightly different than for processors. In addition to developments in nanomagnetic memories, scanning probe technology is providing new ways of nanoscale surface patterning that allow for high-density storage systems.

Nervous fast-profit stock markets push industries towards short-term strategies and cut back on long-term research. Today, most non-industrial research groups are interested in playing it safe as well: they prefer to do 'fundable' research related to industrial needs, which is usually not innovative. This situation fosters a never-ending series of fads and fashions and hampers the flourishing of new ideas. A new élan for long-term, high-risk research and creative scientific genius is needed to make the leap towards the nanoelectronic era.

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3

Nanomaterials

3.1 INTRODUCTION

A. ten Wolde and J. Schoonman¹

A general trend in materials science consists of striving to consciously design materials by preparing solids with predefined and specific characteristics, based on empirical rules and (or) on theoretical considerations. At present, the science and technology of nanoparticles and nanostructured solid materials play an important role in universities, research institutes and industrial laboratories. Special disciplines in physics and chemistry that are concerned with materials composed of particles of nanometer dimensions have recently developed and dedicated scientific journals have appeared already. Fundamental physics and chemistry, as well as materials science and engineering, are involved in advancing the level of understanding and the possibility of controlling atomic arrangement and hence properties.

Nanoparticles, here defined as particles having a length scale of 1 to 100 nm, exhibit new or improved properties compared to the corresponding bulk material. This makes them attractive for applications such as quantum dot lasers, (electro)luminescent devices, novel solar cells, gas sensors, resistors and varistors, conducting and capacitive films, high-temperature superconductors and thermoelectric, optical and magnetic materials [Kruis, 1998a].

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At present, many ways exist to synthesize nanoparticles [Edelstein, 1996]. A traditional route is mechanical ball milling [e.g. Schwartz, 1998]. The advantages of gas-phase synthesis processes are discussed in section 3.5.1. After the synthesis, the particles are collected as a powder or deposited on a substrate.

An artist's impression of gas-phase synthesis and subsequent deposition is shown in figure 3.1.1. Powder can be collected using filtration or electrophoretic or thermophoretic condensation (section 3.2.2). Due to their large surface-to-volume ratio, nanoparticles are very reactive. The particles tend to both agglomerate and oxidize, which causes a substantial handling problem. In order to protect them from oxidation they can be embedded in, for instance, a polymer or a glass, handled in an inert atmosphere or protected by a thin coating.

Nanostructured materials (also called nanophase materials) are different from crystalline, microstructured, and amorphous solids because of the scale of order. In crystalline solids, the atoms are neatly stacked and this order extends to macroscopic dimensions. Microstructured materials show only structural variation (morphology) on a micron scale. In nanostructured materials, this microstructural variation has decreased to nanoscale dimensions. Finally, amorphous material exhibit short-range order only: the average distance between neighboring atoms or molecules corresponds to the material density. Because the nanoscale lies in between the microscopic and the atomic scale, it is also referred to as the mesoscopic domain (meso = Greek for middle).

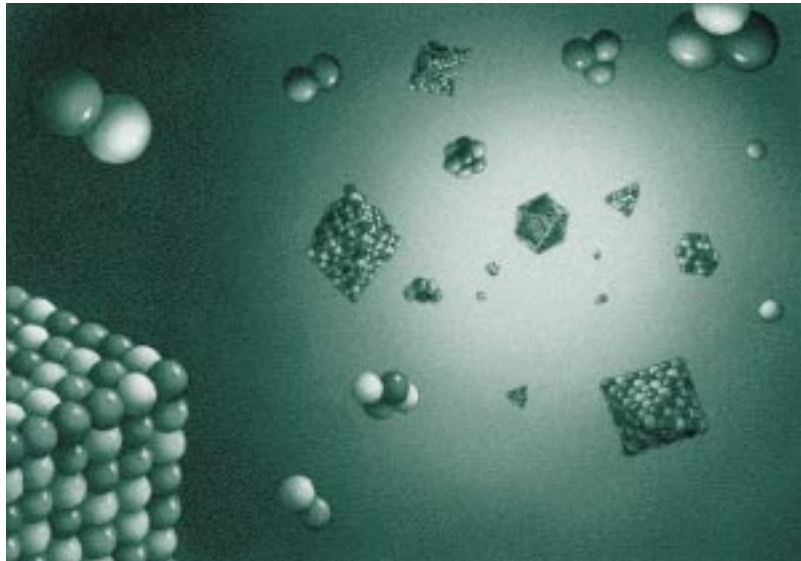
Examples of nanostructured materials are nanoporous, nanocrystalline, nanocomposite, and hybrid materials. Nanoporous materials have nanosized pores. A nanocrystalline material consists of many nanosized crystalline domains. A nanocomposite material contains two or more phase-separated components with a morphology of spheres, cylinders or networks with nanodimensions. Hybrid materials are constructed from a combination of polymeric organic components and inorganic or ceramic components that are chemically interconnected on a molecular level (section 3.3). Both the size of the nanostructures and the scale of order within them affects the material properties. Nanostructured materials are distinguished from conventional polycrystalline materials by the size of the structural units that compose them. They often exhibit properties that are drastically different from those of conventional materials. In many instances, this is a result of the large fraction of grain boundaries – the boundaries between the nanoparticles – in bulk materials, and hence by the percentage of surface atoms. Due to the *large surface area*, bulk properties become governed by surface properties. In nanostructures, a substantial fraction of the atoms are located at or near a surface. This surface – or interface – can border on the embedding matrix, on a nanoparticle, on air or on vacuum in the case of a pore or defect. The size range of 1 to 100 nm implies a number of atoms per particle varying from several to ten million or more. For the smallest sizes, the surface-to-volume ratio becomes very large. For instance, for close-

packed spheres the percentage of surface atoms is about 80% for a 50-atom particle, and is still 20% for a particle containing as many as 2000 atoms. On the other hand, if the particles have dimensions comparable to the wavelength of the electrons, phonons, magnons etc. inside the material, *quantum mechanical effects* predominate. A particle becomes a quantum dot (section 2.3), and quantum confinement leads to a change in the density of states. The macroscopic properties (electronic, optical, electrical, magnetic, chemical and mechanical) of materials can thus be affected substantially by changes in the nanostructure. These changes can be exemplified by [Rittner, 1997a]:

- increase in electrical conductivity in ceramics and magnetic nanocomposites
- increase in electrical resistivity in metals
- increase in magnetic coercivity (representing the resistance to demagnetization) down to a critical particle size in the nanoscale regime
- below this critical particle size, a decrease in coercivity, leading to superparamagnetic behavior (section 3.2.3)
- increase in hardness and strength of metals and alloys
- enhanced ductility, toughness and formability of ceramics
- blue shift in optical spectra of quantum-confined particles
- increase in luminescent efficiency of semiconductors.

Figure 3.1.1

An artist's impression of nanoparticle synthesis by condensation in the gas phase. For a color print see page 241.



Other reported changes include lower melting temperatures and higher catalytic activity [Kruis, 1998a]. Accordingly, various properties that have always been considered as material constants inaccessible to engineering, have now become subject to human manipulation: the tailoring of 'fundamental' material properties has become possible.

3.2 MATERIALS

3.2.1 NANOSTRUCTURED CERAMICS

*J. Schoonman*²

Introduction

The ceramics industry is now some 7000 years old. The field of ceramics and composites containing ceramics was once 50% or more of the materials experience of humanity and is set to rise to this level again when metals diminish in importance (being non-renewable materials). Humanity is in the midst of exponentially rising increases in technological knowledge inherent to the use of new materials [Ashby, 1982]. Although making reliable scientific and technological predictions in a time of such rapid change is difficult, this section will show how ultrafine powders contribute to this development.

The field of ceramics can be divided into structural ceramics, functional ceramics and bioceramics. Structural ceramics are used for their mechanical properties. Several simple concepts for structural ceramics relate in particular to the theoretical strength of the materials. For functional ceramics, the use arises from other than mechanical properties and one needs to consider the electrical, magnetic, and optical properties in relation to the nano- or microscale morphology. As it turns out, only a limited range of new materials is of current interest for advanced structural ceramics, while practically the whole periodic table of elements is available for the development of functional ceramics. Finally, bioceramics (biocompatible ceramic materials for bone implants, artificial hips, etc.) will not be separately discussed. They are considered to be functional ceramics and their morphological aspects are essentially the same as for the other ceramic materials discussed.

Structural ceramics

Many applications require strong materials. How does one select suitable ceramic materials for future development with this purpose in mind? The mechanical properties of structural ceramic materials can be described in terms of the theoretical strength. Hence one needs to look for materials with a high Young's modulus³. In general, the Young's modulus decreases with the bonding strength at the atomic level. This means that in principle, materials with covalent bonding are preferred, followed by materials with ionic bonding, then by metallic and finally by Van der Waals bonding. However, close-packed structures are also favorable. Since covalent structures usually form open networks, while ionic and metallic structures usually have close-packed structures, this is a conflicting situation. Finally, large surface energies are also favorable, but it is difficult to measure this property or to assess its relative value. An unexpected but important expression derived for the theoretical strength of a ceramic

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³ one of the most important
elastic constants of materials,
defined as the tensile stress over
the tensile strain

material with regard to the surface energy predicts that a suitable material must have a low molecular weight [McColm, 1995]. This means that with regard to structural ceramics, one needs to look for covalent and ionic ceramic materials consisting of one, two or three elements from the following three series from the periodic system (appendix 3): Li, Be, B, C, N, O, and F; Na, Mg, Al, Si, and P; and finally Ti, V, Cr, Mn, Fe, Co, Ni, Zn, and Zr.

Attractive properties are not the complete key to the adoption of improved or new materials. Two additional criteria are required for a proper selection of structural ceramics. First, the 'product triangle' interrelates not only material availability and specific properties, but also stresses their relation to fabrication technique. Second, one needs to consider in how well these materials can be fabricated with a well-defined morphology, so that their actual strength approaches the predicted theoretical value. Controlling the morphology leads the way to properties that are the basis of many 'high-tech' applications. This makes the production of nanostructured materials an exciting area for the materials industry. In addition to improved hardness of the end product, well-defined nanostructured ceramic materials exhibit improved ductility at elevated temperatures due to reduced internal friction ('superplastic ceramics'), and a reduced melting point. These properties are important for processing.

In addition to the synthesis and characterization of nanosized particles [Marijnissen, 1993], densification methods should be able to prevent particle coarsening. The intrinsic driving force for densification is often represented by the so-called sintering pressure. Sintering is the formation of dense, compacted materials. The sintering pressure is inversely proportional to both the particle size and the width of the pores between the particles. A high intrinsic driving force for sintering therefore requires compact materials of ultrafine powders with narrow pores to start with. The application of external pressure acts as an additional driving force for densification, which can be used to further reduce sintering time and temperature. There are several techniques of pressure-assisted sintering, namely hot isostatic pressing (HIPing), hot pressing, sinter forging, and dynamic compaction. In sinter forging a uniaxial pressure is applied such that the sample is free to move in the lateral direction. In dynamic compaction either shock (explosive dynamic compaction) or pressure waves (magnetic pulse compaction) are applied. The latter two techniques, especially, lead to morphologies in which the grain size remains in the nanometer regime (smaller than 100 nm) and the materials properties are substantially improved. Recent examples are given in the literature [Boutz, 1995; Boogerd, 1995; Carton, 1998; Jak, 1996].

It is expected that as a new frontier in particle and aerosol research, nanoparticle research has significant potential for scientific breakthroughs and technological innovations in the area of structural ceramics.

Functional Ceramics

This section emphasizes applications related to the dynamic behavior of ionic and electronic species in electroceramic materials, and applications related to optoelectronic properties. Electronic quantum confinement effects in nanoparticles and magnetic materials are discussed in section 3.2.3.

Concerns regarding adequate supplies of hydrocarbon fuels and the negative impact of emissions on the environment have stimulated interest in alternative means for energy conversion, conservation, and storage. The materials research and development for a variety of energy conversion, conservation, and storage devices is covered by the field of solid-state ionics. The needs for research on the use of nanostructured materials for these applications are listed at the end of this section [Tuller, 1997]. For example, the most attractive means for storing power is by electrochemical means, that is in rechargeable batteries based on electroceramics. The source of electricity can be photovoltaic, wind or fuel powered generators, and the combination of conversion and storage techniques would allow a decentralized approach in our energy demand. When hydrocarbon or hydrogen fuels are used, ceramic-based fuel cells promise roughly double the fuel conversion efficiency and considerable reduced emissions compared to internal combustion systems. Ceramic electrochromic materials can be used to develop 'smart' windows, which allow for considerable energy conservation in the heating and cooling of buildings by electrochemical control of visible and infrared radiation transmission through the windows. Chemical gas sensors based on electroceramics provide feedback to insure optimal combustion with respect to conversion efficiency and reduced emissions in internal combustion engines. In electroceramic and optoelectronic materials, current is either conducted by ionic charge carriers alone, or simultaneously by ionic and (photo-excited) electronic carriers. Usually, ionic diffusion proceeds via lattice defects, because diffusion in the bulk is slower than diffusion along grain boundaries. The reason for this difference is that atoms at interfaces (i.e., in the grain boundaries) are located in two-dimensional defects and relaxed from their regular lattice positions. If a large fraction of the atoms are present at the grain boundaries, the bulk properties of a material will be governed by surface properties. This is actually the case for nanostructured materials, in which usually 20 to 50% of the bulk is interfacial volume. This solid state is different from the crystalline and glassy states. As a consequence of this large fraction of interfacial volume, defect densities will be larger than in regular bulk materials [Maier, 1987]. In addition, it is well-known in the materials community that in a polycrystalline solid, diffusion along the grain boundaries often occurs orders of magnitude faster than the corresponding diffusion in the grains [Tuller, 1995].

Hence the decrease in length scale of the primary particles into the nanometer regime results in improved electrical conductivity. Just as with structural ceramics,

functional ceramics need a method of densification that prevents particle coarsening. Magnetic pulse compaction as well as dynamic compaction have proven very effective. Rechargeable ceramic batteries, ceramic electrochromic devices, chemical gas sensors, and ceramic fuel cells depend on optimal electrical properties, and these can be further improved compared to bulk properties by engineering of the material's grain boundaries.

In addition to manufacturing homogeneous dense nanostructured materials, nanopowders also allow the manufacturing of films of nanoporous electrodes. The enormous surface area per unit of geometrical surface area can be exploited by coating the nanoparticles with a light-absorbing dye. This concept was developed by Grätzel and co-workers for the dye-sensitized organic solar cell, which has attracted wide-spread attention, especially in Europe (section 1.2) [O'Regan, 1991; Hagfeldt, 1995].

Recent technological developments in the area of nanoparticles are revolutionizing the field of ceramics with new applications for this age-old material. The chemical and physical properties of nanostructured materials can be strongly influenced and controlled by the size and shape (and the variations therein) of the particles and the pores that make up the structure. It is expected that tailoring of the fundamental properties of nanostructured materials will aid in revolutionizing the materials industry. The examples presented here represent only a selection (section 3.10). The concepts can also be applied to investigate new phenomena such as increased ranges of non-stoichiometry⁴ and the modified segregation of impurities, while new nanostructured composite materials for catalysis and electrocatalysis are being developed to allow cleaner production technology. In addition, quantum-confinement effects such as an optical blue-shift could be used for electrochromic displays. The development of nanostructured materials with exciting properties depends on the outcome of the following research needs [Tuller, 1997]:

- pursue an understanding of the potential sources of enhanced ionic motion along grain-boundaries in both pure and multiphase nanostructured materials
- investigate the dependence of the defect generation and the degree of non-stoichiometry on particle size and on the interface-to-volume ratio
- study the effect of quantum confinement, grain-boundary structure and composition on electronic carrier concentration and mobility
- test and investigate the potential of nanostructured catalyst systems for providing enhanced gas-solid reactions and selectivity
- compare the performance of conventional solid solution insertion electrodes against nanostructured materials
- examine the influence of nanosize features on optical absorption and reflectivity of insertion electrodes that might be used in electrochromic devices
- evaluate alternative processing routes (vapor phase, solution chemistry, electrochemical) for achieving desired tailored structures and compositions.

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⁴ non-stoichiometric compounds have non-integral numbers of atoms in their formulae, such as the high-temperature superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO)

3.2.2 NANOSTRUCTURED SEMICONDUCTOR THIN FILMS

A.P.L.M. Goossens⁵

Introduction

At present, the novel possibilities provided by nanostructured materials have also been utilized in functional thin films. In these films it is particularly the strongly enhanced surface area, when compared to the geometrical area, that provides a large catalytic interface. When brought into contact with gases or liquids, nanostructured thin films can effectively convert chemical substances. New chemical bonds may form (polymerization) or existing ones may break (dissociation). Also, electron transfer reactions (redox-reactions) may proceed at an increased rate. By making use of the catalytic activity of nanostructured interfaces, devices such as solar cells, batteries, sensors, and air/water purifiers have been constructed. In general, the efficiency of these devices depends strongly upon the quality of the films. Therefore, the deposition techniques employed are of paramount importance. In particular, chemical vapor deposition is discussed below as a versatile tool for thin film synthesis of specified crystallinity, morphology, and defect chemistry.

A good example of these developments is the advent of nanostructured titanium oxide (TiO_2) thin films and their use in a variety of devices such as electrochromic displays, photovoltaic solar cells, photocatalytic reactions, and lithium ion batteries. In this case, the extreme enhancement of the surface area and the complicated electronic potential inside the nanostructure together induce important changes in the properties of the titanium oxide material. In addition, the surface area enhancement allows monolayer attachment of functional molecules with a high volume concentration. For instance, so-called 'heterodyade' molecules can be attached for optical switching. These molecules can be electrically addressed and quickly absorb or emit an electron, changing color when they do so. Other functional molecules are employed in photovoltaic solar cells. In that case, dye molecules with a strong optical absorption in the visible and near-infrared range are attached to the nanostructured titanium oxide surface. The dye molecules become excited by absorbing a light quantum (a photon). From this state they can inject an electron into the titanium oxide. If the lifetime of the molecular excited state is long and the rate of regeneration of the dye is fast, efficient charge injection from the dye molecules into the titanium oxide conduction band is possible. Nanostructured solar cells with characteristics comparable to the well-known amorphous silicon solar cells have been realized with this novel device. In Europe, several companies produce these cells on a laboratory and pilot level; commercialization is foreseen in the near future. Nanostructured titanium oxide without dye is used in photocatalytic air purifiers. In Japan, tiles coated with this material are produced for application in houses and cars. In these devices, it is the competition for available active

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surface sites that governs the rate at which contaminating particles are decomposed. Only a nanostructured material can provide a sufficient density of active surface sites.

Nanostructured titanium oxide has also been employed as an anode material in lithium ion batteries. In this case the extremely enhanced surface area speeds up the lithium intercalation⁶ rate spectacularly and offers a high storage capacity. Battery systems with anodes based on this material are already being commercialized and may conquer a substantial fraction of the lithium battery market.

Other semiconductors with nanocrystalline morphology include gallium phosphide and boron phosphide. The former is made porous by electrochemical etching of single crystals, like in porous silicon, but the latter can be grown directly in the gas phase using whisker growth techniques (see below). Many of the characteristic features of nanostructured materials are determined by the details of the synthesis. Below different strategies are briefly reviewed.

Wet-chemical synthesis of nanoscale semiconductors

In order to synthesize nanostructured semiconductors, two wet chemical strategies have been developed. First, a single crystal is etched in aqueous solution. This is a standard technique for the production of porous silicon. Second, semiconductor nanosized particles can be formed by a conventional sol-gel technique. A sol is a suspension of colloids in a liquid (see also section 3.4). Sol-gel technology comprises a wide range of experimental approaches. Successful application of this method has been reported for solar cells [O'Regan, 1990]. In this method, materials containing the desired precursors are mixed in a controlled ratio to form a colloidal solution. Subsequently, coagulation of the colloid particles is achieved by changing conditions such as the temperature or the composition of the liquid. They precipitate on a substrate surface and agglomerate to form a porous film. Usually, a heat treatment is required after deposition of the particles to increase the adhesion of the film to the surface. However, this treatment leads to particle coarsening and sintering.

A narrow and reproducible particle size distribution is important for many applications of nanoparticles in general, and in particular if their (re)activity depends upon particle size, as for instance in catalysis. This distribution is largely determined by process conditions of the preparation method. Nucleation and growth kinetics of small particles in a liquid phase are often determining (but unfortunately poorly understood) phenomena. A narrow size distribution usually results if nucleation takes place in a short time interval. However, in many cases particle size and shape distributions are adjusted by trial and error, with very limited possibilities at present for a predictable and reproducible result.

Nucleation events are extremely sensitive to contaminating particles and minute changes in temperature, composition etc. So one could take extreme

6 the reversible release and take up of ions

measures such as using only ultra-pure chemicals, very well-defined mixing and clean rooms. Another, perhaps more sound approach, is to circumvent difficulties by designing particle formations that are not determined by the reaction mechanism (kinetics) but by the natural tendency of the particle-liquid systems to evolve towards the most stable end situation for a given composition, temperature and pressure (thermodynamics). This evolution is driven by the entropy of the system, which is maximized in the final state. For simple systems the entropy is a measure of disorder. However, more complex systems can actually exhibit spontaneous ordering (self-ordering) and in general the entropy simply indicates the probability for a specific configuration to occur. A valuable inspiration for controlled nanoparticle synthesis in a liquid phase could come from microemulsions. They are thermodynamically stable and upon mixing the precursors they spontaneously approach the size distribution uniquely determined by temperature and mixture composition.

Chemical vapor deposition synthesis of nanostructured semiconductors

As an alternative for wet-chemical techniques, gas-phase methods have increasing interest because they allow improved control over the process parameters (section 3.5.1). As a result, the quality of the product improves as well. The variation in particle size and chemical composition of particles (i.e., their doping level and crystal structure) is reproducible and usually closer to the desired properties than is obtainable with wet-chemical techniques. Before discussing a few selected pathways for gas-phase formation of nanostructured materials, some general aspects of gas-phase synthesis need to be introduced. In conventional chemical vapor deposition (CVD) synthesis, gaseous precursors react either homogeneously or heterogeneously (section 3.5.1). This depends on the specific experimental conditions. In homogeneous CVD, particles form in the gas phase and diffuse toward a cooled surface on which they form a porous film. In heterogeneous CVD, the solid is formed on the substrate surface, which catalyses the reaction and a dense film is formed. In order to deposit nanosized or nanostructured materials, modified CVD techniques have been developed. Several of these will be presented here.

Vapor-liquid-solid growth

In a vapor-liquid-solid (VLS) growth experiment, nanosized metal clusters are deposited on a substrate to catalyze a heterogeneous reaction. This 'activation' of the surface is usually achieved by dipping the substrate for a few seconds in a metal-ion-containing solution and (if necessary) subsequent heating. The catalytic effect of the metal spots can be initiated by various chemical reaction mechanisms [Givargizov, 1987]. For instance, the reactants may dissolve in the metal and crystallize there when the solution becomes too concentrated, leading to the formation of a solid whisker of boron phosphide (figure 3.2.1). Boron

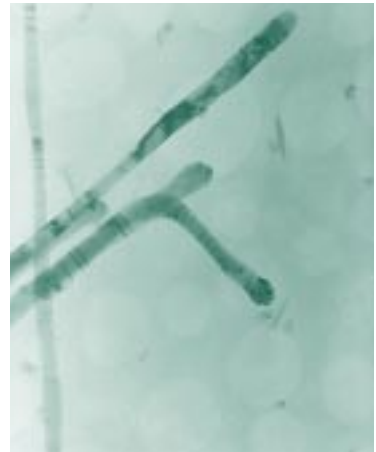
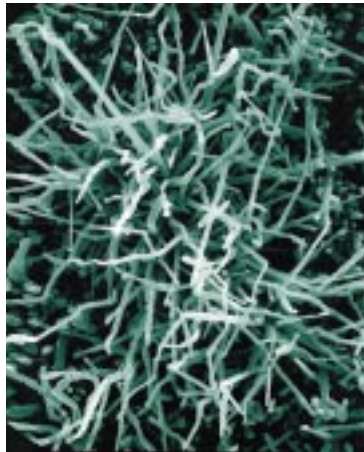
phosphide is a little-known compound semiconductor that crystallizes in the zinc-blende structure⁷. It can be deposited by epitaxial growth (section 2.3) on crystalline silicon [Goossens, 1991; Goossens, 1992]. With vapor-liquid-solid growth, whiskers of boron phosphide can be formed on graphite, silicon or other substrates. A transmission electron microscope (TEM) magnification of a single boron phosphide whisker is shown in figure 3.2.2. It is clear that nanoscale dimensions are readily achieved. The length of these whiskers is about three orders of magnitude larger than their thickness, but the aspect ratio depends strongly on the deposition temperature and the duration of the formation reaction. Moreover, as is always the case in vapor-liquid-solid growth, the whiskers are monocrystalline and prefer growth in a certain direction. These were grown to be used in advanced photovoltaic solar cells.

Figure 3.2.1 (left)

Scanning electron microscope (SEM) image of a graphite substrate covered with boron phosphide whiskers obtained with vapor-liquid-solid growth. The diameter of the whiskers is approximately 50 nm. The substrate has been metallized with either nickel or silver. Without this, a dense polycrystalline boron phosphide film would have been formed; the presence of nanosized metal catalyst spots completely changes the reaction mechanism and the concomitant morphology.

Figure 3.2.2 (right)

Transmission electron microscope (TEM) magnification of individual boron phosphide whiskers such as in figure 3.2.1. The background shows the grid on which the whiskers were collected after removing them from the original substrate. Reprinted with permission from [Goossens, 1995]. Copyright 1995 ESME – 23, rue Linois – 75724 Paris cedex 15.



Particle-precipitation aided CVD

Particle-precipitation aided CVD (pp-CVD) is an important route to synthesize nanoporous films [Dekker, 1994]. In this method, the CVD reaction conditions are set such that particles form by condensation in the gas phase and collect on a substrate, which is under different conditions than the gas phase and allows heterogeneous nucleation. Depending on the process conditions, dense, porous, and fractal surface morphologies can be obtained.

When films of nanoparticles are required on a substrate, the usual method is to insert the substrate in the aerosol flow (an aerosol is a gaseous suspension of solid or liquid micro- or nanoparticles). A large part of the aerosol will, however, pass by. In order to increase the collection of these particles on a substrate, a driving force is applied by cooling the substrate (thermophoresis, the net movement of particles towards regions with a lower temperature) or by applying an electric field (electrophoresis). In thermophoresis-driven particle-precipitation aided CVD the substrate temperature is set slightly below the temperature of the reacting gases. The resulting ‘condensation’ on the surface induces a

7 the same tetrahedral structure as diamond, but with the two different atoms alternating instead of carbon atoms only

particle concentration gradient such that directed diffusion towards the substrate takes place. Temperature differences between 10 and 50°C usually suffice for an appreciable particle precipitation rate on the substrate, which can be as fast as 50 to 100 µm per hour. In electrophoresis-driven particle-precipitation aided CVD, the small electric charge carried by the formed particles is utilized by applying an electric field. This field accelerates the particles towards the substrate. This method requires a conducting substrate that is connected to an electrode: the device is called an electrostatic precipitator. If the charge on the particles is too small, additional ultraviolet illumination can be applied to create more photo-induced charge carriers.

Laser CVD

At present, laser CVD is among the most advanced methods for synthesis of nanostructured surfaces [Bauer, 1991]. Since powerful CO₂ or excimer lasers are required, only laboratory-scale facilities are operational to date. However, because the quality of the CVD products is very high, laser CVD has good potential for future industrial application. In conventional CVD experiments, particles formed in the gas phase usually stay long enough in the hot reaction zone to collide and to form polydisperse⁸ aggregates. This is not the case in laser CVD. By applying a laser beam as energy source, the reaction zone is strongly reduced to a few millimeters or less in a cold-wall reactor. When the reactant gases are injected perpendicular to the beam the time during which they react is very short. When the residence time is close to or below the average collision time, the rate at which particles stick together (sintering) is strongly suppressed, which results in the formation of monodisperse⁹ nanoparticles. By mounting a substrate just outside the reaction zone, the formed particles will land there (because of the previously discussed thermophoresis process) and create a nanoporous film. For example, laser-CVD synthesized particles containing silicon, carbon and nitrogen (Si-C-N) can be deposited on a copper surface using a tunable CO₂ laser and employing an organo-silicon compound and ammonia (NH₃) as precursors. Both precursor molecules have internal vibrations (Si-N and N-H) that can be excited by the absorption of the CO₂ laser radiation of 10.6 µm. This type of minute experimental control over the excitation of specific chemical bonds in the precursors discloses fascinating pathways to advanced gas-phase synthesis. By simply tuning the laser wavelength, reaction mechanisms and concomitant morphologies of the CVD products can be manipulated in great detail, which offers opportunities for exploring a whole new range of materials with unexpected properties.

8 of many different sizes

9 of equal size

Summary and conclusions

Investigating the fascinating properties of nanostructured materials is of great importance both from a fundamental and an applied perspective. However, the physical and chemical properties are strongly related to the synthesis route employed. Both wet-chemical and gas-phase techniques are being utilized. Wet-chemical techniques offer the advantage of relative simplicity and many years of experience in colloid science. However, there are limitations in the choice of materials (oxides only!) and the level of contamination of the end product. Advanced gas-phase deposition techniques can be successfully employed to synthesize, for instance, nanostructured thin films of both non-oxides and oxides. Because of the excellent control over the supply and mixing of reactant gases, the environment and the reaction mechanism, nanostructured materials with reproducible properties can be synthesized with gas-phase methods. Vapor-liquid-solid growth can be employed to form a dense collection of nanowires on a variety of surfaces, whereas nanoporous thin semiconductor films can be obtained from particle-precipitation-aided CVD. Finally, the utilization of lasers for material synthesis offers unsurpassed control over chemical synthesis of semiconductors and other materials in the gas-phase and offer, therefore, new challenges for material scientists.

3.2.3 METAL NANOPARTICLES

*L.J. de Jongh*¹⁰

Metal nanoparticles or clusters are of great interest for fundamental science as well as for potential applications. The increase in surface-to-volume ratio has enormous consequences for the properties of metal particles. Most, if not all chemical reactions occur at the surfaces (interfaces) of materials. This explains, at least in part, why metal particles can be used advantageously in industrial catalysts, and, more generally, their special role in chemical synthesis and reactivity. In addition, important problems such as chemisorption and physisorption of molecules on metal surfaces can be fruitfully studied with metal nanoparticles, both experimentally and theoretically.

Quantum size effects

The size-evolution of the physical properties from atom to bulk may also be related in part to the variation of the surface-to-volume ratio. However, in addition to these 'classical' effects, the quantum-mechanical properties of the electrons play an equally important role. These so-called quantum-size effects can be understood most simply by realizing that according to the particle-wave duality of quantum mechanics, a conduction electron in a metal behaves both as a particle and as a wave. (The particle-wave duality implies that according to

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both quantum theory and experiments, particles sometimes behave as waves, while on the other hand a wave sometimes behaves as a beam of particles. For instance, electrons can form an interference pattern whereas light can be absorbed in particle-like packages called photons.)

Treated as a wave phenomenon, the electron in a metal has a wavelength of one to a few nanometers. The wave character of the electron will become predominant as soon as it is confined to a region in space of that size, and this is precisely what occurs in a metal nanoparticle! It is the underlying reason why familiar bulk-metallic properties disappear when the size of the particle is reduced towards the nanometer regime. In terms of the energy-level diagram of conduction electrons in a metal, the metal-nonmetal transition corresponds to the replacement of the (pseudo-) continuous energy band structure appropriate for the bulk solid, by the discrete energy level structure characteristic for electrons confined to such a small volume (figure 2.3.1). The average level separation in the electronic energy diagram is inversely proportional to the volume of the particle and is on the order of 10 meV for a particle of about 1000 atoms, when each atom contributes one conduction electron to the cluster. The term 'quantum-wells' or 'quantum-dots' is used for these restricted geometries (see also section 2.3). In terms of the quantum-well picture, a small particle of sodium, for instance, can be regarded in many respects as a giant atom (or molecule). The electrons are confined by the walls of the particle, which present a force field that is approximately aimed to the center of the particle. This is similar to the concentric force field inside an atom provided by the electrostatic attraction between the negatively charged electron and the positively charged nucleus (Coulomb force). Thus, the building-up principle of electrons in such a cluster is very similar to that underlying the periodic table of elements (appendix 3). Just as in atoms, the electrons line up in shells and the chemical properties depend heavily on the number of electrons in the outer shell. Indeed, strong differences in reactivity have been observed for clusters with fully filled or only partially filled electron shells! An attractive feature of clusters in this respect is evidently, that the number of electrons (atoms) per cluster can surpass by orders of magnitude the number of elements in the periodic system.

The discrete electronic energy level spectrum of clusters (section 2.3) also forms the basis for several of the expected possibilities for future applications. For instance, light-induced transitions between occupied and unoccupied energy levels are responsible for the optical properties of materials: the distances between energy levels determine in which region of the electromagnetic spectrum these properties will be located. The possibility of varying the level separations in clusters by changing their volume opens up the way to tunable optical properties. Several research groups hope to use clusters to obtain eventually lasers in so-far-unavailable spectral ranges. It should be added here that these aspects are by no means restricted to metal nanoparticles, but apply to insulating

or semiconducting clusters just as well. In the latter the semiconducting energy gap has been shown convincingly to be a sensitive function of size in several cluster materials such as cadmium sulfide (CdS) and cadmium selenide (CdSe) clusters.

Experimental analysis of the physical behavior of metal nanoparticles

So far, the discussion has been centered on properties of particles isolated from one another and from their (direct) environment. Do metal nanoparticles indeed show these properties? In order to check this experimentally it is of interest first to summarize briefly the various methods by which small metal particles may be produced. In fact, the only method to produce fully isolated individual clusters is by atomic or molecular beams. In this method the metal (or other material) is evaporated under high-vacuum conditions or in an inert gas atmosphere. The beam of atoms is subsequently expanded through a nozzle, whereupon they condense into clusters, which can be studied while they are freely flying or after deposition onto a suitable substrate, such as graphite. The freely suspended clusters in the beam are indeed fully isolated, but the disadvantage is that they can be analyzed with only a few experimental probes, mainly spectroscopic measurements. Such experiments have proven to be of immense value, and have greatly advanced our fundamental knowledge of clusters, but with regard to applications the possibilities are very limited.

For more practical purposes one would want to use metal particles produced by other means, in particular on supports or in matrices. The advantage is the availability of macroscopic amounts of sample, the disadvantage that the interaction with the supporting medium has to be assessed. A great variety of synthetic methods exist. Metal clusters can for instance be produced by aerosol techniques, by vapor deposition, by condensation in rare-gas matrices, by chemical reactions in various supports such as zeolites (nanoporous materials that have since long been used for catalytic cracking in petroleum refineries), silica (SiO₂), aluminum oxide (Al₂O₃), or polymer matrices. Many different metal-nonmetal composites such as ceramic metals have been obtained with metal particles of nanometer size and larger. In alternative approaches, metal particles are stabilized by a coordinated bond formed by the electronic interaction with an organic or inorganic molecule (the ligand). Examples are metal colloids and metal cluster compounds.

Surface screening

Fortunately, knowledge about interactions between clusters and supports has greatly advanced in recent years. In the last decades, very extensive efforts have been devoted in surface science to the experimental and theoretical studies of the interactions between molecules and metal surfaces. As a general rule of thumb, it appears that these interactions are very important but limited for

the most part to the outermost layer of metal atoms, that is those directly bonded to the adsorbed molecules. This can be understood on basis of the extreme screening power of conduction electrons in a metal. As a consequence of the screening, the atoms located deeper than one or two layers inside the metal do not 'feel' the presence of a surface at all. This screening has also been found for metal clusters. As soon as a particle consists of several layers (i.e., for about 100 atoms or more) only the atoms at the surface layer are affected by the interaction with the surroundings. So the apparent conclusion is that such metal nanoparticles may indeed be regarded as collections of 'bulk' metal particles, although with a smaller effective diameter because the properties of the outer layer are affected by the surroundings. This is important for purposes of application, which will in most or even all cases involve assemblies (arrays) of metal particles embedded in some medium.

Regular model systems of metal nanoparticles

Up till now, most of the stacking of the metal particles in experimental cluster assemblies has been random, as in the metal-nonmetal composites, the metal colloids, and in matrix-stabilized clusters. However, more and more efforts are being directed towards obtaining regular, periodic arrays of preferably identical metal particles. Such possibilities are offered by zeolites, in which the metal particles can reside in regularly spaced holes in the structure. Even more promising are metal cluster compounds, many of which can be obtained in crystalline form. Since these chemical compounds have a homogeneous composition, the metal particles in a given metal cluster compound are all identical (with sizes up to a few hundreds or even a few thousands of atoms). They are also chemically stabilized by coordinated bonds with a shell of surrounding material. Thus, they can be regarded as ideal model systems for macroscopically large assemblies of identical metal nanoparticles.

Another possible approach uses major recent advantages in nanolithography. It has already proven possible to obtain two-dimensional arrays of regularly spaced metal particles with sizes of about 10 nm using evaporation techniques [Chou, 1997]. Alternatively, surfaces may be prepared by etching techniques or a thin coating in order to enable the anchoring of metal cluster molecules or colloidal particles at equal spacings. Such a two-dimensional array of metal particles should allow researchers to address the particles individually, for instance with the tip of a scanning tunneling microscope (STM, see section 5.2), and thus may play an important role in nanoelectronics. More generally, metal-nonmetal composites can be expected to display novel conducting and dielectric properties, in particular if the particles are identical in size and regularly spaced.

Magnetic nanoparticles

This section concludes with a few remarks on magnetic particles. They do not necessarily relate to bulk magnetic metals such as iron, cobalt or nickel, and may even be pieces of materials that are magnetic insulators in bulk form.

Although small ferromagnetic particles (having a tendency for parallel alignment of their magnetic moments) do exist, most effort has been concentrated on their antiferromagnetic counterparts (antiparallel alignment).

Application as a high-density magnetic recording material requires a high magnetization as well as a high coercivity (representing the stability of the magnetization). When the particle size in nanostructured magnetic materials is reduced, the coercivity increases until a maximum is reached when the particle size coincides with the size of a magnetic domain, typically tens of nanometers.

For instance, iron powder with a crystallite size of 13 nm showed a 90-fold increase in the coercivity. Further reduction of the particle size leads to a sharp decrease of the coercivity [Kruis, 1998a]. The particles usually consist of a single magnetic domain, so that a net magnetic moment per particle results, but the thermal activation is strong enough to overcome the magnetic ordering in the structure and magnetic behavior is lost. This so-called superparamagnetic effect is already becoming of some importance to the magnetic recording industry. Challenging fundamental problems that are still under investigation include surface magnetism, the effects of interactions between the metal particles and their surroundings on the magnetic properties, the magnetism of macromolecules, and the quantum tunneling of the magnetic moment of a nanoparticle. Finally, magnetic nanoparticles can also be used for magnetic fluids (section 3.4).

Brief outlook for possible applications of metal nanoparticles

Metal nanoparticles have interesting *catalytic properties*. They can also lead to *novel conductors*. The enormous versatility of nanocomposite materials, which can have conducting and nonconducting components, offers the possibility of obtaining materials that combine metal-like conducting properties with non-metallic other properties such as mechanical stiffness and optical absorption. In the area of *nanoelectronics*, metal particles may be arranged randomly or regularly-spaced in the form of one-, two- or three-dimensional arrays. Their volume and the degree of electric insulation is tunable. Such arrays can be obtained either chemically or by nanolithography, and they may be used for high-density data storage. Metal nanoparticles can also be used to improve the properties of existing applications. The use of magnetic clusters or magnetic macromolecules may greatly reduce the size of magnetic particles as used presently in applications. The study of fundamental issues such as the interactions between metal particles and their surroundings should be of great help in optimizing the end-products. Finally, just like nanostructured ceramics, nanostructured metals are ultrastrong: their hardness increases monotonically with

decreasing grain sizes down to about 10 nm. Below that value, computer simulations predict a softening due to a large number of atomic 'sliding' events at the grain boundaries, which will ultimately pose a limit on how strong nanocrystalline metals may become [Schiøtz, 1998].

Recent review papers on metal clusters are [Halperin, 1986] and [de Heer, 1993]. A theoretical review is given by [Brack, 1993]. Relevant books on the subject are [Sugano 1995], [Haberland, 1994], [Schmid, 1994], [de Jongh, 1994], and [Dormann, 1992].

3.3 COMPOSITES: HYBRID COATINGS

H.A. Meinema and M.P. Hogerheide¹¹

This contribution is a slightly adjusted translation of a Dutch paper published under the title *Hybride coatings, nieuwe materialen met veelzijdige toepassingen* (Hybrid coatings, new materials with multi-functional applications) in *Klei, glas and keramiek* (Clay, Glass and Ceramics) **18**, No. 9, pp. 20 – 25 (1997)

Introduction

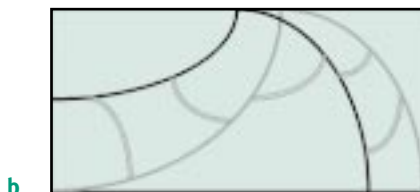
An interesting development in materials technology, with a great potential for industrial applications, is the development of new inorganic-organic hybrid materials. These are materials which combine the specific favorable properties of inorganic/ceramic materials (high mechanical strength, wear- and abrasion resistance) with those of organic/polymeric materials (flexibility and impact resistance). Hybrid materials are constructed from a combination of polymeric organic components and inorganic or ceramic components that are chemically interconnected on a molecular level, and are mostly prepared by a combination of sol-gel and polymerization techniques. Using this approach, materials with completely new and/or superior properties are being developed, materials that cannot be obtained with classical procedures such as the addition of inorganic fillings and/or fibers in coatings and polymers.

The research on hybrid materials was initiated in the eighties, especially by the group of H. Schmidt, presently director of the INM-Institut für Neue Materialien in Saarbrücken, Germany [Kaseman, 1994]. Globally, the research on hybrid materials is receiving increasing amounts of attention from both fundamental and more applied research groups [Kaseman, 1994; Novak, 1993; Sanchez, 1994; Amberg-Schwab, 1996, and references cited therein]. Since there are many highly diverse (potential) opportunities for applications, the attention from the industry has strongly increased. The most important applications are to be found in the area of functional coatings. Because of their special composition, these coatings possess a unique combination of properties of

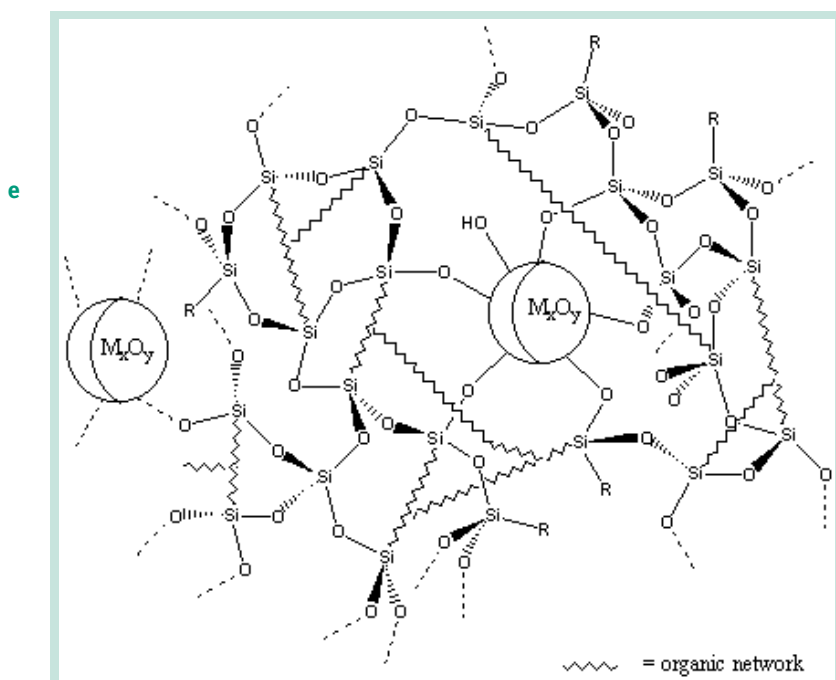
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Figure 3.3.1

Different types of hybrid materials.



— inorganic network
— organic network
— non-covalent bridge



the inorganic and organic components, for instance hydrophobic, hydrophilic, anti-fogging, anti-fouling, anti-adhesive and/or Teflon-like properties in combination with hardness and scratch and abrasion resistance. The combination of mutually chemically interconnected (interpenetrating) organic and inorganic networks results in coatings with a very low permeability for gases and liquids [Amberg-Schwab, 1996]. Hybrid coatings are mostly transparent in the visible and can be cured at relatively low temperatures (100 to 350°C), in contrast to the traditional inorganic sol-gel coatings, which are cured at much higher temperatures (over 600°C).

What are hybrid materials?

Hybrid materials are constructed from a combination of inorganic and organic components that are chemically connected on a molecular level. Various combinations are possible, roughly distinguished as follows (figure 3.3.1):

- a** Organic polymers embedded in an inorganic matrix. These materials can be regarded as a ceramic sponge filled with polymer. Interpenetrating networks are formed that may be connected by polar interactions and hydrogen bridges, but not by direct covalent chemical bonds.
- b** Interpenetrating organic-inorganic networks connected by covalent chemical bonds.
- c** Inorganic networks modified with organic groups.
- d** Alternating, chemically connected inorganic and organic units.
- e** Above mentioned systems with homogeneously dispersed and covalently bonded oxidic nanoparticles such as silica (SiO_2), aluminum oxide (Al_2O_3), titanium oxide (TiO_2), and zirconium oxide (ZrO_2).

Synthesis methods

Depending on the chemical composition and the reactivity of the inorganic and organic building blocks from which the hybrid network is constructed, coatings of mentioned types **a** through **e** can be obtained. Organosilicon compounds, especially tetra-alkoxysilanes $((\text{RO})_4\text{Si}$ with R = methyl or ethyl) function as the most important building blocks for the inorganic network. Under acidic or basic conditions they hydrolyze by reaction with water, in a sol-gel process, and condense into silica networks. Under acid conditions, rapid hydrolysis and slow condensation leads to the formation of mainly $-\text{SiOSi}-$ chains with few branches and many OH groups bonded to the chains. Under basic conditions the hydrolysis and condensation reaction proceed rapidly and simultaneously, resulting in the formation of silica nanoparticles. Mainly for steric reasons – the central silicon atom is less approachable – the hydrolysis reactions with tetraethoxysilane $((\text{C}_2\text{H}_5\text{O})_4\text{Si})$ proceed at a slower rate than with tetramethoxysilane, $(\text{CH}_3\text{O})_4\text{Si}$. Tetraethoxysilane is usually preferred because the slower hydrolysis step is easier to control and because the ethanol formed is less toxic than methanol. In

addition to silica, various metal oxides can be part of the inorganic network. These oxides can be formed simultaneously with the silica-network in a sol-gel process by controlled hydrolysis of the corresponding metal alkoxides. These metal alkoxides are much more sensitive to hydrolysis than tetra-alkoxysilanes. Rapid hydrolysis with water will often result in the formation of a metal hydroxide/metal oxide precipitate. For a more controlled hydrolysis process, modification of the metal alkoxides to less reactive species is required. This is achieved by the introduction of alkyl groups consuming more space around the central metal atom – e.g., iso-propyl instead of methyl and ethyl – in combination with space-filling ligands, such as carboxylates, complexing to the metal. By a proper choice of reagents and process conditions it is possible to incorporate silicon, aluminum, titanium and zirconium oxides in the inorganic part of a hybrid network, either individually or in combinations.

For the preparation of hybrid coatings of type **a**, the inorganic alkoxides are hydrolyzed under the proper conditions of solvent, temperature and acidity (pH), and mixed with the organic (pre)polymer. This solution is applied onto a substrate such as a metal, glass or plastic, and subsequently cured to form a hybrid coating, either thermally at temperatures varying between 100 – 350°C, or using ultraviolet (UV) light or an electron beam in the case of a suitable coating composition. During the curing process, the inorganic network and the organic network are constructed simultaneously by condensation and polymerization reactions, respectively, and under the formation of an interpenetrating network. Actual examples of this type of hybrid materials are combinations of polyacrylates with silica networks.

Functionally substituted organosilicon compounds act as coupling reagents for the chemical linking of inorganic and organic components. For the preparation of hybrid materials of type **b** use is made of organotrialkoxysilicon compounds, $\text{RSi}(\text{OR}')_3$. Here R is an organic substituent that is covalently bonded to the silicon atom by a carbon atom with a reactive functional group attached to it, that allows the formation of a direct covalent bond with the organic network. The organic and inorganic networks are interconnected by hydrolysis and condensation reactions while splitting off of the OR' groups ($\text{R}' = \text{methyl or ethyl}$). Reactive functional groups include epoxide, (meth)acrylate, amino or isocyanate, which can be incorporated into polymeric organic networks. Epoxide groups can be attached to (poly)amines, polycarbon acids and polyalcohols; (meth)acrylate groups co-polymerize with other (meth)acrylates; amino groups can be attached to (meth)acrylates, epoxides and isocyanates, and isocyanate to amines and alcohols. Some representative examples of organotrialkoxysilicon coupling reagents are listed in table 3.3.1.

name	reactive group	formula
γ -glycidoxypropyltrimethoxysilane	epoxide	
γ -aminopropyltriethoxysilane	amino	
γ -methacryloxypropyltrimethoxysilane	methacrylate	
γ -isocyanatopropyltrimethoxysilane	isocyanate	

Table 3.3.1

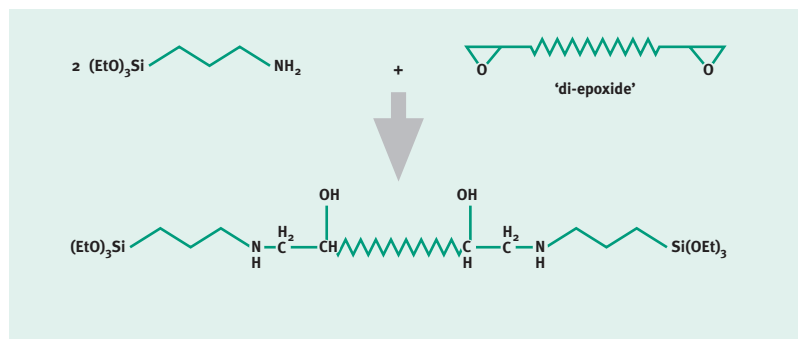
Four organotrialkoxysilicon coupling reagents used for the preparation of type **b** hybrid materials, each one containing a different reactive group.

Hybrid materials of type **c** are obtained by hydrolysis and condensation reactions of a tetra-alkoxysilane, with or without the presence of aluminum, titanium and/or zirconium alkoxides, in combination with alkyl and/or phenyl substituted organosilicon compounds, $\text{RSi}(\text{OR}')_3$, $\text{R}_2\text{Si}(\text{OR}')_2$, with R = alkyl, phenyl; R' = methyl, ethyl.

Hybrid materials of type **d** can be obtained by the reaction of functionally substituted organosilicon coupling reagents either with each other or bifunctionally with an organic molecular unit (figure 3.3.2). The bis-triethoxysilane compound thus obtained can be connected with the inorganic component by a hydrolysis-condensation reaction.

Figure 3.3.2

A synthesis route for hybrid materials of type **d**. Two molecular units of an organosilicon coupling agent (upper left) react with a bifunctional organic molecular unit (upper right) to form a bis-triethoxysilane compound (lower molecule).



The above mentioned hybrid systems **a** through **d** can be modified into transparent coating systems of type **e** by incorporating homogeneously dispersed oxidic nanoparticles in the material. Silica nanoparticles, especially, are easily accessible since they can be commercially obtained. The composition of hybrid nanocomposite materials of type **e** is schematically depicted in figure 3.3.1. Hybrid coatings of types **a** through **e** can eventually be obtained from the basic components by subjecting a reaction mixture of a specific composition under the proper conditions to a thermally, UV or electron-beam initiated curing process. During this process, the organic network is constructed by means of classical organic polymerization reactions, with or without organosilyl functions (RSi≡) covalently incorporated in the organic network. The inorganic network is formed by sol-gel condensation reactions after hydrolysis of silicon alkoxides, possibly in combination with hydrolysis of metal alkoxides and/or oxidic nanoparticles added to the reaction mixture.

Functional properties and applications

Hybrid materials are very suitable for application as coatings on a highly diverse spectrum of substrates including glass, ceramic, plastic, wood, and metal. Before curing, the coating material consists of a clear alcoholic solution that can easily be processed by classical application techniques such as dipping, spraying, or spin-, flow- or roller coating.

As described before, the researchers have many degrees of freedom concerning the chemical composition of the coating solutions and hence of the intended eventual properties of hybrid coatings and coating-substrate combinations. This makes hybrid coating systems unique. Applied research in this area is aimed at tuning the composition of the basic chemical components and of the

Figure 3.3.3

*Strengthening of plastic: Transmission loss, 1-T (%), as function of the number of wear cycles in a Taber-abraser test on a hybrid coating. The results indicate that especially coatings of type **e** show a very high abrasion resistance due to the incorporation of oxidic nanoparticles. Whereas polycarbonate subjected to the Taber-abraser with a wheel weight of 0.750 kg showed a transmission loss of approximately 50 % measured at 600 nm after 500 cycles as result of wear, polycarbonate equipped with a good hybrid coating (2-4 μm thick) of type **e** showed a transmission loss of only 4 to 5 %. For comparison, approximately 3 % loss was found for borosilicate glass.*

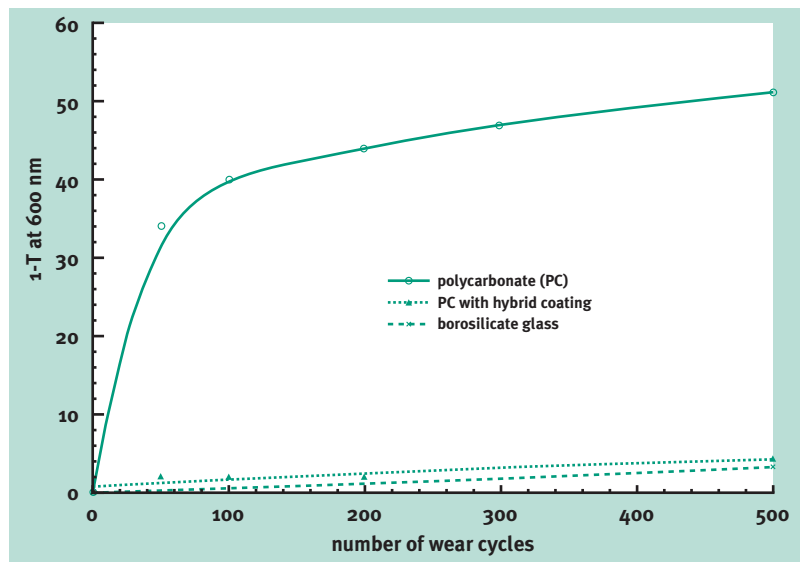
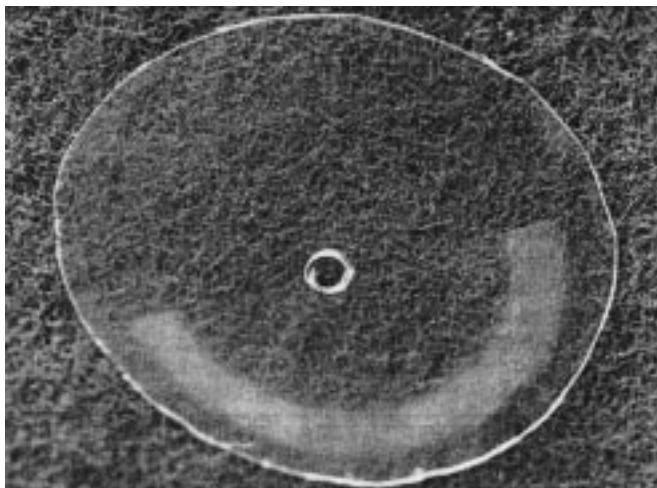


Figure 3.3.4

Scratch- and abrasion resistant hybrid coating on polycarbonate. Result of a Taber-test after 500 wear cycles (see also figure 3.3.3). The uncoated half of the test sample clearly shows the effects of wear, while the coated part is not visibly affected.



corresponding curing conditions in such a way that coating-substrate combinations are obtained that exhibit the desired properties. In this way flexible, transparent, scratch-resistant, abrasion-resistant and chemically resistant coatings can be obtained for various applications on soft plastics (e.g., polycarbonate, polyacrylate), especially by incorporating preformed nanoparticles of silica and metal oxides. Opportunities for applications include the replacement of glass by much lighter polycarbonates – especially in ophthalmic glasses, head lights and car windows – and the replacement of soft plastics by a material equipped with a harder scratch-and abrasion resistant coating. Representative abrasion resistance results for various types of hybrid coatings of type **d** and **e** on polycarbonate are depicted in figures 3.3.3 and 3.3.4.

Specific surface properties can be transferred to the coating surface by incorporating organosilicon compounds with functional properties. In this way hydrophobic, Teflon-like and fat repulsive coatings can be obtained with dirt-repelling, anti-adhesive, and anti-graffiti properties by incorporating fluorine-containing organic groups bonded to silicon. An artist's impression of a graffiti-repelling hybrid coating is shown in figure 3.3.5. The effect of a water-repulsive hybrid coating on steel is demonstrated in figure 3.3.6. The development of thermally stable hybrid coatings with anti-adhesive, water-repulsive, chemical-barrier and/or flexible properties on various substrates for highly specific applications is attracting widespread attention. By incorporating ionic and/or polar substituents, coatings with anti-fogging properties can be obtained. Another example is the development of transparent hybrid coatings with anti-growth properties for underwater applications of optical instruments. In recent years, especially the INM in Saarbrücken has been active in the area of applied research on hybrid coatings.

Conclusions

Hybrid coatings are constructed from organic and inorganic components that are connected on a molecular level and/or are mutually dispersed. This approach offers many possibilities for chemical diversification of the molecular structure and thus of specific properties. Coatings can be obtained that combine the properties of organic polymers, such as plasticity, flexibility and impact resistance, with those of ceramic materials, such as mechanical strength, chemical resistance, crash and abrasion resistance. In principle, these coatings can be applied on all possible substrates including glass, ceramics, plastics, metals, and wood. Hybrid coatings potentially offer many opportunities for the development of new products.

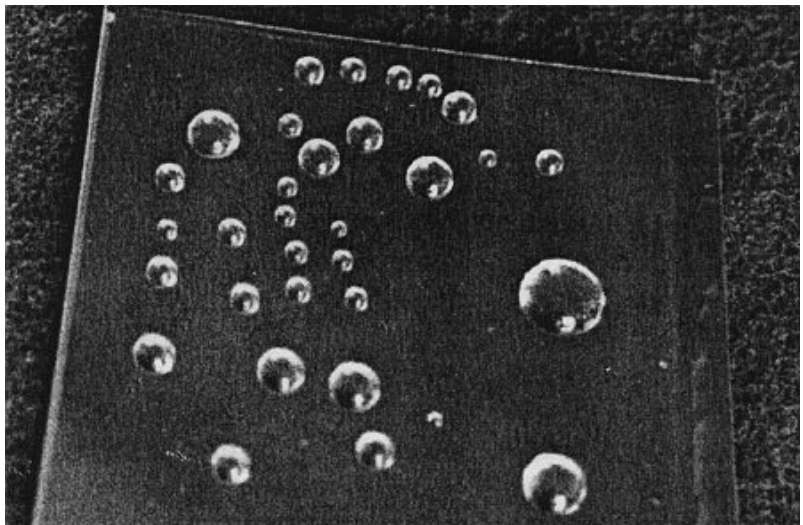
Figure 3.3.5

Artist's impression of a graffiti-repelling hybrid coating. The uncoated areas (right) are covered with paint. The coating (left) repels the paint so that it cannot adhere and forms drops to minimize the contact area with the surface. For a color print see page 328.



Figure 3.3.6

Water-repulsive hybrid coating on steel.



3.4 COLLOIDAL DISPERSIONS

A.P. Philipse¹²

WHAT ARE COLLOIDS?

Colloid science studies the physics and chemistry of finely dispersed matter. Colloids are traditionally defined as particles (or other objects such as droplets, bubbles or thin films) with at least one dimension roughly in the range of 1-1000 nm. Just like 'nano', the term 'colloid' refers to the dimension only. Hence nanoparticles can be viewed as colloids smaller than 100 nm. (Colloid science has a long tradition involving nanosized particles; not all that is 'nano' is necessarily new!). Examples of colloid materials are gold colloids, colloidal silica, and aluminum oxide powders in the colloidal size range.

Due to their small dimensions colloids exhibit thermal Brownian motion (diffusion) [Dhont, 1996]. Due to the large surface area, the interaction between colloidal particles in the liquid phase is dominated by surface forces such as Van der Waals attractions, and repulsions due to the particle charge. The balance between these forces strongly depends on details of the particle surface (charge, roughness, adsorbed species) and the liquid composition (ionic strength, polarity, added polymers). Colloids easily aggregate to form large flocs, networks or gels. The control and understanding of this aggregation is a major issue in colloid science and of great practical importance.

A suspension of colloids in a liquid is called a dispersion or a sol. Such a dispersion often looks turbid due to adsorption or scattering of light by the colloids, and viscous because the particles hinder the flow of the carrier fluid. This viscous behavior led Graham in 1861 to the term 'colloid' derived from the Greek $\kappa\omicron\lambda\lambda\alpha$, 'glue-like'. The term is still appropriate in view of the fundamental tendency of colloidal particles to stick together.

Familiar dispersions are milk, body fluids such as blood, cosmetics such as toothpaste, and the ink used for printing this book. We also find a large variety of inorganic colloids, such as clay particles, iron oxides on computer disks and in magnetic fluids, pigments in paints, and powders for technical ceramics.

Fundamental properties of colloidal systems are often studied using particles with well-defined shape and size, prepared by chemical synthesis. However, colloid science not only studies chemical preparation methods, but also physical properties of dispersions such as the flow behavior, settling of particles, filtration, phase transitions [Lekkerkerker, 1993] and gelation phenomena [Poon, 1996]. Important input is also obtained from computer simulations [Frenkel, 1996] and statistical mechanics. This wide scope of colloid science is unavoidable: finely dispersed matter is encountered in many disciplines and applications. Figure 3.4.1 shows several examples of inorganic particles synthesized with colloid chemistry.

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Figure 3.4.1

Examples of inorganic particles synthesized with colloid chemistry.

a SEM micrograph of crystallized silica spheres (radius $R = 50$ nm).

b Magnetite particles,
 $R_{\text{core}} = 5$ nm,
 R_{total} (with a silica shell) = 40 nm.

c Hematite spindles
(length = 500 nm, width = 125 nm).

d Gold particles,
 $R_{\text{core}} = 15$ nm,
 R_{total} (with silica shell) = 75 nm.

e Zinc sulfide particles,
 $R_{\text{core}} = 5$ nm,
 R_{total} (with silica shell) = 20 nm.

f Boehmite rods
(length = 190 nm, width = 9.8 nm).

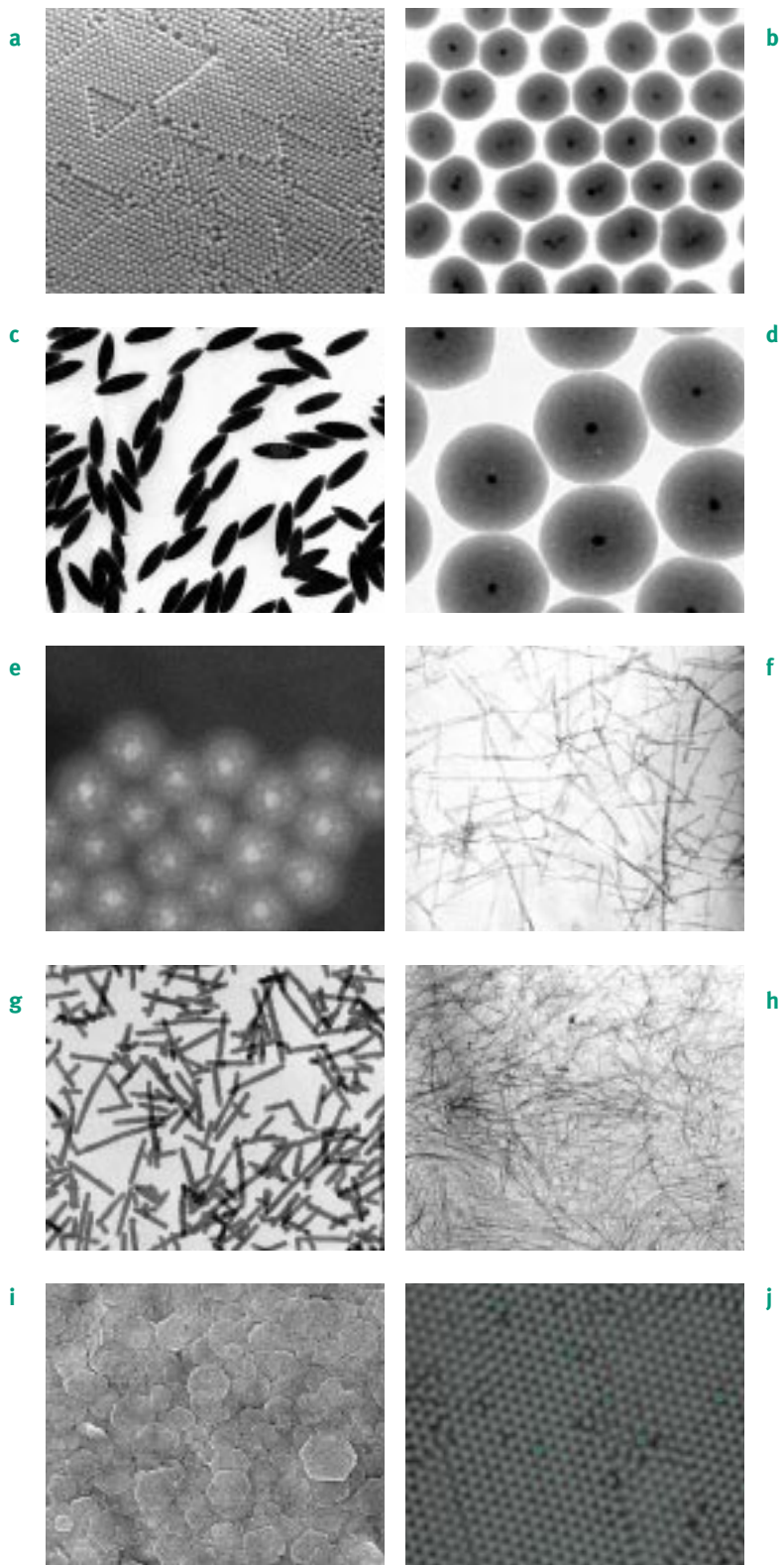
g Boehmite rods with a fluorescent silica shell
(length = 323 nm, width = 46 nm).

h Imogolite fibres
(length ~ 600 nm).

i Gibbsite platelets
(diameter = 170 nm, width = 6 nm).

j Fluorescent silica particles,
Dark grey spheres: $R_{\text{core}} = 100$ nm,
 $R_{\text{total}} = 215$ nm.
Green spheres: $R_{\text{core}} = 195$ nm,
 $R_{\text{total}} = 492$ nm.

Courtesy of C. van Kats, A. van Blaaderen, M. van Bruggen, F. van de Kooij, L. Donselaar, L.M. Liz-Marzan, and G. Koenderink, Van 't Hoff Laboratory, Utrecht, The Netherlands.



General

One method of preparing inorganic colloids is mechanical milling of granular material. This is still industrial practice. However, direct preparation of colloidal particles in the liquid phase is becoming increasingly important. An example is polymerization and subsequent precipitation in precursor solutions of salts. In principle (but often not in practice), such chemical methods allow control of particle size and shape.

Wet-chemical synthesis of nanosized particles is as old as chemistry itself and the difficult problem of how to obtain a dispersion of non-aggregated particles with well-defined properties has been studied in colloid science at least since the beginning of this century. Aggregation leads to settling of large flocs or the formation of space-filling gels. This gelation is essentially the 'sol-gel' process (a term also coined by Graham), which is now widely studied to fabricate materials from small particles.

A striking trend is the gradual division of (inorganic) colloid science into the younger disciplines of 'sol-gel science' and colloid physics. In sol-gel science the (applied) research on the chemistry of small-particle dispersions is rapidly expanding, while in colloid science itself the emphasis seems to shift to colloid physics, using a smaller palette of colloidal model systems. Such a division is not without risks. Sol-gel science may have to reinvent wheels if it is unaware of the colloidal tradition, whereas colloid science may lose the feeling for the 'real dispersions', its *raison d'être*. An active policy of strengthening links between physics and chemistry of colloidal dispersions is required.

Functional colloids

Interesting developments take place for functional colloids. This functionality can be chemical, physical or simply labeling. Particles diffusing in a liquid phase may have a chemical functionality, for example, chemically selective organic molecules or polymers grafted onto the colloid [Nechifor, 1997]. A physical functionality occurs when particles respond sensitively to external forces. Examples are magnetic dispersions ('ferrofluids') that can be manipulated by a magnetic field, and so-called electrorheological fluids that solidify when an electric potential is applied. Optical functionality is the goal of studies on the possible use of ordered arrays of colloidal particles ('colloidal crystals') [van Blaaderen, 1997] to obtain structures with a photonic band gap that exhibits strong selective reflection at visible wavelengths.

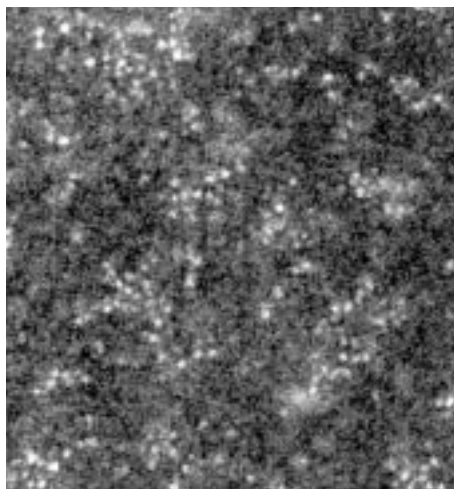
A colloidal particle may also function as a label or a carrier by which one can manipulate an attached molecule or polymer. For example, the colloid may carry catalytic surface groups that are easier to recover from a chemical process in a reactor. Developments are taking place to recover the (magnetic) particles by

means of a magnetic field.

There is also increasing activity in the synthesis of nanosized noble-metal particles such as gold for labeling of biomolecules [Buining, 1997] and their localization with electron microscopy (figure 3.4.2). Here particle sizes of about 1 nm are required because larger labels hinder migration of the labeled molecule.

Figure 3.4.2

High-angle annular dark-field scanning transmission electron micrograph (HAADF-STEM) of gold nanoparticles with an average diameter of 1.4 nm. Reprinted with permission from [Buining, 1997]. Copyright 1997 American Chemical Society.



Composite colloids

Inorganic particles in a liquid phase are often covered with a brush of polymers to prevent or slow down flocculation. Ink is an example. For nanoparticles, the organic surface layer comprises a significant part of the particle volume. They may be called organic-inorganic composite particles or core-shell colloids. The dispersability of such particles in organic solvents is an important topic in colloid science [Vrij, 1995]. Many variations on this theme can also be identified in material science, such as the synthesis of hybrid materials, the mixing of inorganic additives in plastics, and the ‘filling’ of rubbers with solid particles. In all cases one attempts to achieve a homogeneous distribution of ‘polar’ particles in an ‘apolar’ environment (like a dispersion of water in oil.) This mixing will become more difficult for smaller particles. In the nanosize range the ‘sticking surface area’ is large. Moreover, aggregates of nanoparticles will be very difficult to disrupt mechanically. Here one has to avoid aggregation by controlling the colloidal forces between the particles before, during, and after mixing.

Composite colloids may also contain cores and shells of different inorganic materials, as in some paints containing titanium cores protected by an amorphous silica shell. Recent developments concern amorphous silica colloids with a well-defined size between 10 to 500 nm that have a small crystalline core (1-10 nm) made of noble metals and magnetic or semi-conductor materials. The core determines the optical, electronic and magnetic properties. The silica shell provides opportunities for easy grafting of surface molecules, improves chemical

stability in a wide pH-range, and keeps the cores at a well-defined distance when the colloids are compacted. This latter feature is of interest for making crystals of colloidal particles [van Blaaderen, 1997].

Particle size distribution

A narrow and reproducible particle size distribution is very important for many applications. Unfortunately, the nucleation and growth kinetics of nanoparticles in a liquid phase is a poorly understood phenomenon. In many cases particle size and shape distributions are adjusted by trial and error, with very limited possibilities at present for a predictable and reproducible outcome. Nucleation events are extremely sensitive to contaminants and minute changes in temperature, composition etc. The particle growth stops when the precursor solution is exhausted. As discussed in section 3.2.2, one can deal with the situation either by using stringent cleanliness and process-control procedures or designing systems that follow a thermodynamically determined route. In the latter case, the system spontaneously approaches the size distribution uniquely determined by temperature and mixture composition. Examples are microemulsions and the formation of nano-gold particles in the presence of sulfur groups that strongly adsorb to the gold surface of the particles.

PROCESSING OF PARTICLE DISPERSIONS

General

When dispersions of colloidal particles are used, they have to be processed, that is, they are pumped, centrifuged, filtered, pressed, extruded etc. Very dilute dispersions can be transported like ordinary liquids. However, at the high concentrations of practical (and fundamental) interest, processing strongly depends on properties and interactions of the dispersed particles. Model dispersions and computer simulations [Frenkel, 1996] are used to investigate processes such as particle diffusion, sedimentation and flow ('rheology'). Still, the understanding of practical systems such as drilling fluids and paints is very limited because of the many components, particle sizes and shapes, and additives.

It is important to realize that these processing techniques, traditional as they may seem in a 'nano context', still present many fundamental problems to modern (particle) science. Processing of nanoparticles in the liquid phase will underline these problems, rather than presenting new ones. For instance, the rheology and separation techniques such as filtration and sedimentation are more difficult to control for very small particles.

Note also that the choice of solvents for the wet processing of small particles, at least on an industrial scale, is limited because of environmental restrictions. Improving processing steps by trial-and-error variation of solvent composition

is no longer a serious option. Fewer solvents on the shelf implies a greater need to understand the factors that determine the dispersability of particles in a liquid.

Polymer-colloid mixtures

Intriguing phase behavior may be observed when colloidal particles are mixed in a liquid phase with non-adsorbing polymers. Colloids and polymers diffuse and occasionally two colloids approach each other closely. If the polymers do not stick to the colloids, they will avoid the narrow gap between the two particles. As a result the pair experiences an unbalanced push of polymers from 'outside', which will narrow the gap further. In other words, the polymers induce an effective attraction between the particles, the so-called depletion force. This somewhat unconventional attraction suffices to induce phase separation and gelation, and also has a marked effect on transport properties such as sedimentation or flow behavior. So addition of 'inert' polymer to a liquid phase system is an interesting possibility to influence processing. (This addition can be made useful in other ways during a later stage of the processing, in which the polymer may also act as a binder or as a supplant of inorganic species during sintering). The depletion force is probably operative in many practical dispersions such as clay dispersions, paints and inks. It has been studied extensively with model colloids [Poon, 1997] and computer simulations but is certainly also of interest for sol-gel studies and dispersions of metallic nanoparticles where free polymers or other species are present.

Non-spherical particles

Colloidal spheres of equal size have been used extensively to study the behavior of fine-particle dispersions. However, many colloids are non-spherical, which inspires the present interest for the preparation and properties of particles shaped as platelets, thin fibers, rods, tubes etc. Practically all dispersion properties (particle settling, viscosity, optical properties etc.) change if one goes from spheres to non-spheres. The changes are even more marked for particles with extreme shapes such as thin discs and long fibers.

Orientation of rods may occur spontaneously for thermodynamic reasons [Lekkerkerker, 1993]. In addition to liquid-crystal polymers, crystals may also form in liquid phases containing inorganic rods and were recently observed for synthetic clay platelets. Furthermore, the flexible orientation of colloidal rods and stiff polymers is an important factor in the processing of dispersions. When shear forces in a pumped dispersion align the particles, the viscosity may decrease considerably. Alignment of rods may also be stimulated by an electric field. Such a preferred particle orientation induces optical polarization effects ('birefringence'). The effect is often reversible, which may be of interest for the possible application of colloidal rods in displays.

Magnetic fluids

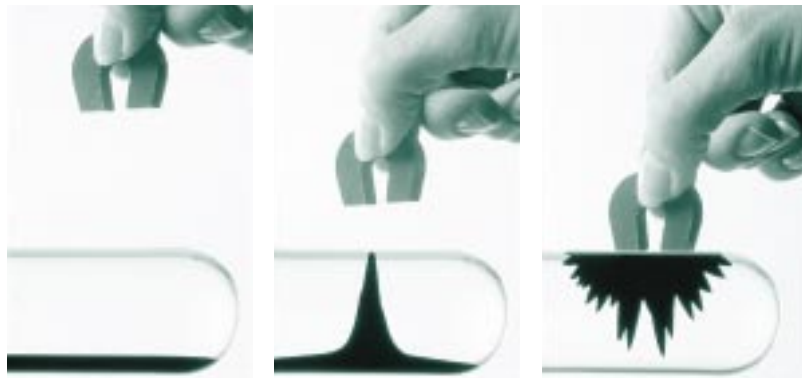
Magnetic fluids (ferrofluids) are concentrated colloidal dispersions of small magnetic particles with a diameter below about 10 nm. In contrast to larger ones, these particles show little tendency to aggregate and form a sediment. Molecular or ionic surface groups can further reduce this tendency by inducing a repulsion between the particles. As a result, the fluids contain finely dispersed materials such as iron oxides (e.g., magnetite) and cobalt. The particles are magnetic sub-domains, which freely rotate in the carrier liquid so that the dispersion has no net magnetization. The colloids can be manipulated with a magnetic field, dragging the liquid phase with them (figure 3.4.3). As a result the dispersion behaves as a liquid magnet, even in strong fields. This makes these fluids suitable as liquid O-rings to seal off rotating devices such as computer disk drives from dust in a nearly frictionless manner. Many other applications have been claimed in about 1500 patents, including mechanical vibration damping in stepping motors, magnetic muscles, dirt absorbers in waste separation facilities, and intrinsically simple couplings for automobile fabrication [BMBF, 1998].

Magnetic fluids are poorly understood in spite of some twenty years of research on these fascinating systems. An incentive for further research is the possible use of such particles in biomedical separation or labeling techniques, and in heterogeneous catalysis. More possibilities of magnetic nanoparticles are discussed in section 3.2.3.

Figure 3.4.3

A magnetic fluid (black) consisting of 10-nm magnetite (iron oxide) particles in solution. In response to a permanent magnet, the fluid inside the test tube flows upward and forms a wedged interface.

Source: Ferrofluidics Corporation/
Ferrosound, Nashua, NH, USA.



NEW BUZZ WORDS, OLD PROBLEMS

New ideas and concepts concerning nanoparticles may quickly find their way from coffee tables to project proposals and public attention. But we should not be misled into thinking that they all represent new problems, as already indicated. Moreover, ideas and expectations about nanoparticles are easier generated than implemented. The practical details often spoil the party. For example, the options for directing a large number of nanoparticles in a dispersion to form a

desired structure such as a dense ceramic, a nanoporous medium or a membrane are limited. One could try to manipulate particles one by one using scanning probes (chapter 5), much like building a house from single bricks.

However, for the fabrication of bulk material this approach is not an attractive option if we want to see some results in the next millennia. Another option is so-called self-assembly (section 4.2). In this case one uses the inherent thermodynamics of the liquid-particle system and hopes that they will organize by themselves collectively (possibly assisted by external fields) into a desired structure. A beautiful example is the spontaneous, purely entropy-driven formation of long-range crystalline order in dispersions of colloidal spheres above a certain ‘freezing concentration’ and the analogous growth of liquid crystals in dispersions of colloidal rods [Lekkerkerker, 1993]. These examples are the outcome of years of laborious research on relatively simple particle shapes. There is certainly every technological and scientific reason to increase research on collective phenomena such as the formation of crystals, glasses and gels in dispersions of small particles. However, one has to be cautious about raising expectations. We have gained some control and understanding of the *average* behavior of large particle populations. However, frequently the variations around the average values are very important as well. Illustrative is the optimistic expectation – probably abandoned by now – in material science that colloidal crystals of equally sized small particles could serve as the basis for defect-free ceramics. In practice, these crystals turn out to have very few cracks indeed, but they are invariably big.

Finally, a piece of important advice to those engaged in nanomaterials: Think occasionally about particles in a ‘non-material’ way. Look at consequences of the fact that the particles have a certain size or shape, rather than what material they are made of. Do not only consider the details of chemical reactions and of the individual behavior of atoms and molecules, but also address the chemically less specific non-covalent surface forces between small particles. This ‘non-material’ approach is indispensable because (colloidal) surface forces are always important for finely dispersed matter.

3.5 SYNTHESIS OF NANOPARTICLES

3.5.1 GAS-PHASE SYNTHESIS

*F.E. Kruis and H. Fissan*¹³

At present, many synthesis routes to nanoparticles exist [Kruis, 1998a]. Gas-

phase processing systems have several inherent advantages. These include

- a very good control over size, shape and crystallinity
- a higher purity than in case of liquid synthesis through improved control over the composition of the environment
- possibility of synthesizing multicomponent nanoparticles because of the convenient way in which the reactants are supplied and mixed
- cost advantages compared to, for instance, vacuum synthesis techniques due to the use of atmospheric or low-pressure conditions
- easier control over the reaction rate and the reaction mechanism through temperature variation of the gas.

VARIOUS METHODS FOR GAS-PHASE SYNTHESIS OF NANOPARTICLES

Synthesis methods based on homogeneous gas-phase nucleation

Most synthesis routes presently in use are based on the production of atoms or small clusters (monomers) that can aggregate to form a particle (condensation). Condensation occurs when the vapor is supersaturated. This means that the vapor becomes ‘too dense’, i.e. the cluster density exceeds the maximum equilibrium density at the given temperature. While ordinary condensation creates a film on a surface, homogeneous nucleation (particle formation in the gas phase) forms particles because there is no surface available. This is made possible by physical or chemical methods. The physical methods involve some form of cooling of the vapor. Homogeneous nucleation can be achieved also by chemical reactions that produce a nonvolatile condensable product. These are usually decomposition reactions initiated by a rise in temperature. Various heating and evaporation methods are possible.

Furnace

The simplest method is to heat an inert heat-resistant container (crucible) containing the material in the form of a liquid or of large solid particles in a furnace. The material evaporates and is carried away by a flowing inert gas. This method can be used for substances having a high vapor pressure at temperatures up to about 1700°C. Nanoparticles are formed by subsequent cooling, such as the natural cooling that occurs after leaving the furnace, or dilution cooling.

Materials with too low a vapor pressure for obtaining appreciable particle formation have to be fed into the furnace in the form of suitable precursors, such

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as organometallics or metal carbonyls. These decompose in the furnace to yield a condensable material.

Laser pyrolysis

In the laser pyrolysis technique (pyr = Greek for fire) a flowing reactant gas is heated rapidly with an infrared laser such as a CO₂ laser. The source molecules are heated selectively by absorption of the laser beam energy, whereas the carrier gas is only indirectly heated by collisions with the reactant molecules. A gas-phase decomposition of the reactants takes place due to the temperature increase, after which the vapor becomes supersaturated and starts to form nanoparticles by homogeneous nucleation. For instance, laser-induced fragmentation of silane (SiH₄) results in silicon nanoparticle formation and decomposition of ironpentacarbonyl (Fe(CO)₅) leads to iron nanoparticles. The main advantage of laser-heating in gas-flow systems is the absence of heated walls, which reduces the risk of product contamination.

Laser vaporization

Laser vaporization of solids uses a laser that evaporates a small area from a solid target in an inert gas flow reactor. It is a useful method for materials with a very high melting point and low vapor pressure.

Flame reactors

Flame reactors employ the flame heat to initiate chemical reactions producing atoms or small molecules that can aggregate to form a particle. The flame route has the advantage of being an inexpensive method, however, usually it yields agglomerated particles and there is a risk of carbon contamination. Most flame reactors are operated at normal pressure, but they can also be operated at reduced pressures in order to decrease the particle size. An example is the oxidation of titanium tetrachloride, silicon tetrachloride or tin tetrachloride in a methane/oxygen flame leading to titanium dioxide, silicon dioxide or tin dioxide nanoparticles. Products with a more complex chemical composition (*e.g.*, nanocomposites) can be also obtained.

In some flame reactors, the agglomeration of formed nanoparticles can be reduced while avoiding oxidation, by covering each particle with a protecting layer which can later be removed. In a sodium (Na) flame for instance, the nanoparticles formed in the flame are immediately encapsulated in a layer of sodium chloride (NaCl).

Plasma reactors

A plasma can also deliver the energy necessary to cause evaporation or initiate chemical reactions. The plasma typically has a temperature of about 10,000°C and decomposes the reactants or even solid powder feeds into ions, atoms, and

radicals. The charges on the particles may prevent further collisions and growth. Nanoparticles are formed upon cooling while the fragments are exiting the plasma region. Many different types of plasmas are in use, such as the direct current (dc) plasma jet, the dc arc plasma, the radio frequency (rf) induction plasma, inductively coupled plasma (ICP), microwave-generated plasma, and a high-current plasma spark between two solid electrodes. Each has its particular merits and applications. A closely related technique is the exploding wire: a wire is vaporized instantaneously in a chamber filled with an inert gas. However, this last method has the disadvantage of being non-repetitive, and usually leads to a large spread in particle size.

Sputtering

Sputtering is a method of vaporizing materials from a solid surface by bombardment with high-velocity ions of an inert gas such as Ar or Kr, causing an ejection of atoms and clusters. Normally, sputter sources are used to produce an ordinary vapor that condenses on a substrate and are operated in vacuum systems with a pressure below 10^{-3} mbar. It was shown, however, that a microwave sputter source can eject nanoparticles of sizes between 5 and 20 nm if the pressure is increased to the millibar range. Sputtering has the advantages that the heating is for the most part limited to the target material and that the composition of the sputtered material is identical to that of the target. The latter is especially important for the synthesis of semiconductors.

The ultra-fine-particle (UFP) machine

*J. Schoonman*¹⁴

A promising new route to nanoparticle fabrication is via gas evaporation of metals in an inert atmosphere. The so-called ultra-fine-particle (UFP) machine is a multi-purpose inert-gas evaporator machine [Hayashi, 1997; Söderlund, 1998]. The machine can produce nanoparticles via gas evaporation in different ways. In addition to metal particles, the machine can produce nanotubes of ferromagnetic particles with diameters of about 20 nm and lengths of several micrometers, and even ceramic particles (TiO_2).

The nanoparticles produced with this UFP machine exhibit the following basic properties:

- they are of high purity, because they are synthesized in a high-purity inert gas atmosphere via a condensation process
- they exhibit good crystallinity, because they are produced under quasi-thermal equilibrium conditions
- a narrow particle size distribution can be easily achieved
- the mean size of the particles can be well controlled
- any element or compound that can be vaporized by the heating sources

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- available in the machine can be transformed into nanoparticles
- the production rate of nanoparticles of a given quality is usually several orders of magnitude higher than for other nanoparticle manufacturing techniques.

The nanoparticles produced in the inert-gas-evaporation chambers of the UFP machine can also be used to deposit nanostructured crystalline films and layered structures. Using an advanced gas deposition (AGD) technique, the particles are directed towards a substrate by a high-speed gas (usually helium) flow via hydrodynamically designed jet nozzles. This method gives rise to excellent adherence and a high packing density and, therefore, to outstanding mechanical and corrosion resistance properties. Stacked layers of magnetic materials with excellent properties have been deposited as well.

With this method, patterned films and nanostructured layers comprising two layers of different nanocrystalline materials are being deposited. Two independent gas deposition jet nozzles, two independent induction heat sources, and a computer-controlled xyz substrate holder are employed. The layers consist of particles with typically 10 to 20-nm sizes in a densely packed morphology.

Several improved properties are:

- improved hardness: gold particles are up to 10 times harder than those produced by other methods
- improved film adhesion for gold films
- flexible materials, for instance for golden spring wires produced by advanced gas deposition
- heat-resistance improved by 300 to 400°C
- improved chemical resistance: weather-safe aluminum films and rust-free iron films
- improved catalysis: gold-coated titanium dioxide particles exhibit improved catalytic behavior.

The ultra-fine-particle technique and the advanced gas deposition technique have many potential possibilities in the field of nanoparticles and nanostructured materials, that have yet to be explored to the full extent.

Synthesis methods not based on homogeneous gas-phase nucleation¹⁵

Nanoparticle formation in the gas phase does not always rely on homogeneous nucleation. When a pulsed laser ablates a solid source, clusters or even larger particles ejected from the surface may flock together. One important characteristic of this method is that the nanoparticles have the same composition as the substrate, which is for some materials difficult to achieve using normal evaporation methods. Another method is the formation of nanoparticles by the evaporation of micron-sized aerosol droplets in which the desired material is dissolved. By choosing a sufficient dilution, nanoparticles consisting of the solid residue

¹⁵ The remaining part of this section has been written by F.E. Kruis and H. Fissan

can be obtained. Electrospray systems are often applied as aerosol droplet generators because they produce very small droplets with a very narrow size distribution in comparison to other spray processes. Droplets produced by electrosprays may explode during evaporation when their electric charge is too high, yielding yet smaller droplets of various sizes that can produce nanoparticles. In addition, initiating homogeneous nucleation inside aerosol droplets can result in many nanosized nuclei within a single droplet. This will yield nanoparticles when the droplet evaporates and the residue material eventually fragmentates in the gas.

Avoiding particle agglomeration

Methods for rapid cooling of the vapor are essential when nanoparticles have to be synthesized and when the formation of hard agglomerates has to be avoided. These agglomerates are formed by partial fusion of particles that flock together, forming material bridges that cannot be broken or dissolved. One of the most successful cooling methods is the so-called inert-gas condensation, in which the nanoparticles are collected on a liquid-nitrogen-cooled surface (a 'cold finger') and are continuously scraped off into a funnel. The powder can be compacted inside the reactor to avoid oxidation by exposure to air. This method has been scaled up and is already been applied in industry, yielding up to 40 tons/month. Expansion of a condensable gas through a nozzle leads also to very high cooling rates. Special nozzle designs can result in a uniform temperature gradient. This leads to a highly uniform cooling rate and thus to nanoparticles with a narrow size distribution.

VARIOUS OTHER ASPECTS OF GAS-PHASE SYNTHESIS

Transformation

Chemical and physical transformations are applied in order to obtain the desired product. In some cases, several chemical reactions are used, one after another. As an example, in the case of gallium arsenide (GaAs) synthesis via direct sublimation is not possible because their evaporation rates are widely different at any given temperature. Therefore gallium nanoparticles are synthesized by evaporation in a first furnace and then reacted in a second furnace with AsH_3 , resulting in gallium arsenide nanoparticles. In addition to the chemical composition, the crystallinity is also important. Usually crystalline particles are required. In lead sulfide (PbS) nanoparticle synthesis, the as-formed nanoparticles are amorphous and non-spherical; they have to be sintered in order to obtain monocrystalline and spherical particles.

Protection

Protection of nanoparticles is important because their large surface area makes them very reactive. This is the main handling problem. In order to protect them from oxidation, they can be embedded, for instance, in a polymer or glassy host, handled in an inert atmosphere or protected by a thin coating. As an example, a method to avoid oxidation of flame-generated nanoparticles is to encapsulate them in the reactor within a material, for instance a protecting layer of salt (NaCl), which can later be removed by washing or sublimation.

Mixing on the nanoscale

Making nanocomposites requires nanoscale mixing of the components. Usually this is not possible when the components are separately collected as powder, due to the presence of big aggregates. Mixing during the reaction or shortly afterwards, when the nanoparticles are still unaggregated or only slightly aggregated, is necessary to obtain a homogeneous mixing. Controlled mixing can be obtained by electrical bipolar mixing, in which two aerosols are separately charged with opposite polarities and then mixed. The aggregation rate of particles of the same component is slowed down by the charging while the aggregation rate of particles of unequal components increases. An example is the bipolar mixing of barium zirconium oxide (BaZrO_3) with the high-temperature superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO), in which the number of BaZrO_3 particles combining with one YBCO particle could be controlled by the charge level on the BaZrO_3 particles.

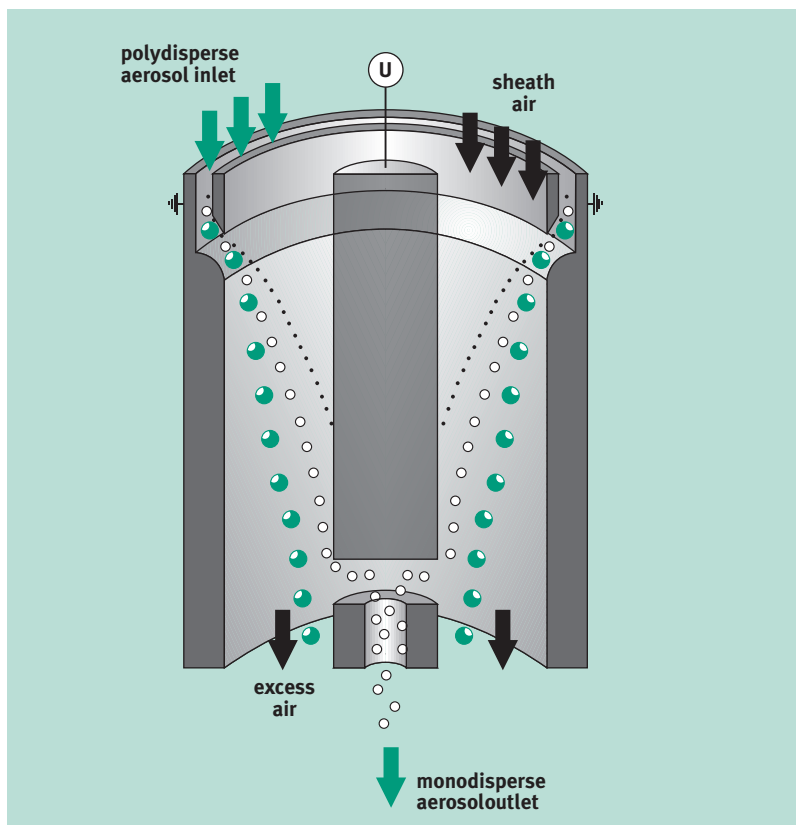
Separation of particles with different sizes in the gas phase

Gas-phase processes yield particles with a broad size distribution, having standard deviations of 1.3 to 1.6. When a narrower size distribution is required, the first process requirement is to make sure that all the particles experience the same time-temperature history. Nanopowders with a narrow size distribution (standard deviations below 1.2) can only be obtained by special techniques using the separation of particles with different size (size fractionation). Nanosized particles are inherently very difficult to separate with filtration or sedimentation.

A reasonably economic technique for size fractionation, being operated at atmospheric pressure, uses a differential mobility analyzer (DMA), schematically shown in figure 3.5.1. The size-selectivity of this apparatus for charged particles is based on their electric mobility. The electric mobility is related to the particle size because it depends on the mass and shape in addition to the charge level. After an experimental comparison of four DMAs, a nanometer-aerosol differential mobility analyzer (Nano-DMA) was designed, optimized for the size range 3 to 50 nm [Chen, 1998]. The performance of the Nano-DMA was optimized and predicted by a numerical model and has been validated experimentally.

Figure 3.5.1

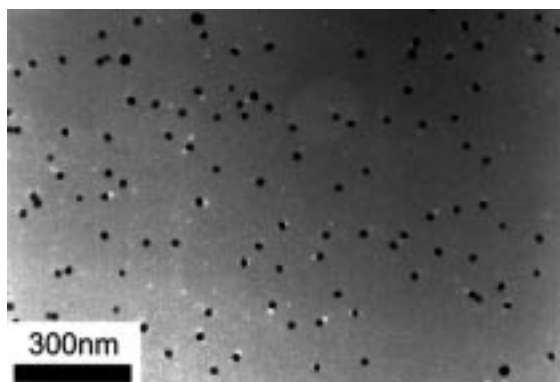
Schematic diagram of a differential mobility analyzer (DMA). The charged particles coming from the polydisperse aerosol inlet are driven towards the central electrode by the electric field. Only particles of one selected size exit through the slit in the electrode, because particles of different size have different trajectories inside the apparatus. Particles of various sizes (between 3 and 1000 nm) can thus be separated from the aerosol flow.



This technique has been applied to produce silver silicon, gallium, gallium arsenide, indium phosphide, and lead sulfide nanopowders with a narrow size distribution. In figure 3.5.2 an example can be seen of size-separated nanoparticles produced in our laboratory. Lead sulfide (PbS) semiconductor particles with a mean size of 18 nm and a standard deviation of 1.14 were produced by sublimation in a furnace, charged using a radioactive source, size-fractionated in a differential mobility analyzer and deposited onto a substrate by using an electrostatic precipitator.

Figure 3.5.2

Lead sulfide (PbS) semiconductor particles with a mean size of 18 nm and a standard deviation of 1.14 after size-fractionation in a differential mobility analyzer (DMA). See [Kruis, 1998b].



3.5.2 LIQUID ATOMIZATION

*J. Schoonman*¹⁶

The possibility of using electric fields to disperse liquids has recently attracted much interest from the scientific community. The subject includes a wide variety of applications, numerous experimental configurations and a large spectrum of liquids.

The electro-spraying of liquids is referred to as electro-hydro-dynamic atomization (EHDA). The atomization by primarily electrical (electro) forces of a liquid (hydro) that is moving (dynamic) during the atomization captures the essence of the phenomena. At present no complete theory exists that describes how the atomization process proceeds as a function of both external (experimental configuration, flow rate, and atmosphere) and internal (fluid properties) process parameters. The fluid properties that are receiving major attention are: electrical conductivity, surface tension, absolute viscosity, density, and dielectric constant.

The process of electro-hydro-dynamic atomization can take place in various atmospheres, using a variety of fluids, experimental conditions, and mechanisms for the production of charged droplets from large (order of millimeter) to very small (order of nanometer) droplets, from polydisperse to monodisperse droplet populations, and from low to high flow rates.

The spray mode of particular interest for the production of nanosized particles and nanostructured materials is the cone-jet mode (often referred to as the Taylor-cone mode). In this mode, the jet coming out of the conical nozzle breaks up into droplets by various mechanisms that depend of the applied potential. High production rates and droplets of reasonably uniform size can be obtained [Meesters, 1992].

Nanosized particles of ceramic materials can be obtained if the aerosol is collected in a heated furnace, depending on the concentration of precursors in the fluids. To date, this 'electrostatic spray pyrolysis' (ESP) technique has been used to synthesize nanosized particles of electroceramic materials for application in solid-state electrochemical sensors, fuel cells and batteries [Vercoulen, 1993]. The method has been modified to deposit thin films of electroceramic material, in which a grounded, heated substrate is used to collect the aerosol (electrostatic spray deposition (ESD)). Depending on the process conditions, the latter technique leads to dense, porous, fractal, and reticulate surface morphologies of sub-micron dimensions. The size of the primary particles usually lies in the nanometer range. The method has also been used to deposit laminar structures of electroceramic materials to form a rechargeable lithium-ion battery or a ceramic fuel cell [Chen, 1997; Chen, 1996; Chen, 1996b; Chen, 1995; Kelder, 1995; van Zomeren, 1994].

The majority of the reported research has focused on oxidic materials that were

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synthesized in air. Non-oxidic materials can be made by changing the ambient atmosphere to an inert one. This is especially interesting for the manufacture of structural ceramics (section 3.2.1), as nanosized particles will lead to products with highly improved mechanical properties.

3.6 CHARACTERIZATION BY HIGH-RESOLUTION TRANSMISSION ELECTRON MICROSCOPY

J. Van Landuyt and G. Van Tendeloo¹⁷

Analysis of nanostructures is challenging, especially because of the number of characteristics that influence the material or device's behavior.

High-resolution electron microscopy (HREM) can provide the required detailed imaging on nanometer scale. In particular, when combined with electron diffraction and x-ray microanalysis, high-resolution electron microscopy enables full characterization of the atomic structure (e.g., the crystal structure), nano- and microscale structures (size, shape, morphology), the chemical composition, and the occurrence of internal defects. It therefore remains an essential and irreplaceable tool for characterization on a nanometer scale. Other high-resolution microscopy techniques such as STM (scanning tunneling microscopy) and AFM (atomic force microscopy) are discussed in chapter 5.

State of the art

One way to perform electron microscopy is to image the electrons transmitted and (or) scattered by a (thin) sample. Transmission electron microscopy (TEM) has reached a resolution level of around 0.1 nm on the most dedicated instruments; most commercial instruments, however, have a resolution around 0.2 nm. This allows for atomic resolution, from which researchers can deduce useful structural information for a wide range of applications. Thus nanostructures can, in principle, be imaged, yielding valuable morphological and detailed structural information. However, at this high magnification, the final image is highly influenced by the interference between phase changes from the sample with those caused by optical aberrations in the lens system. The raw data contain combined information on the sample filtered by the microscope itself. The information on the sample can only be retrieved by suitable interpretation and retrieval techniques. Useful image interpretation requires numerical image processing and computer simulation of the images, using the dynamic theory of electron diffraction and experience with crystallographic aspects that can give rise to special effects on images and diffraction patterns. These diverse image treatment facilities are now readily available and applicable in dedicated laboratories for high-resolution electron microscopy. Information on size, size distribution, and on the substructure of nanostructures can thus be obtained at the

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highest magnifications after appropriate interpretation of the data. Nevertheless, one should always be aware that the image interpretation is not merely a straightforward ruler measurement on a photograph. Appropriate interpretation of high-resolution electron microscopy not only provides information on the structure but also on its internal defects. If the sample is crystalline, the image can usually be complemented by diffraction data providing straightforward information on the crystal structure [Amelinckx, 1997]. Analysis of the local composition of nanosized particles or agglomerates is possible by coupling available accessories such as x-ray microanalysis configurations and electron energy loss (EELS) spectrometer set-ups to a nanoprobe lens configuration.

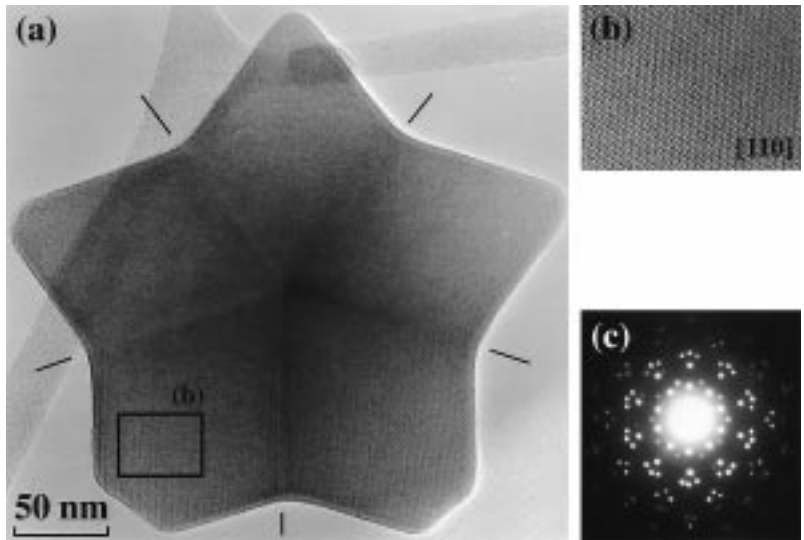


Figure 3.6.1
C₆₀ nanoparticle produced by the aerosol method. The fivefold symmetry is visible in both the direct image obtained with electron microscopy (a) and – for a diffraction expert – in the diffraction image obtained with the same instrument (c). High-resolution electron microscopy allows direct imaging of the atomic structure (b).

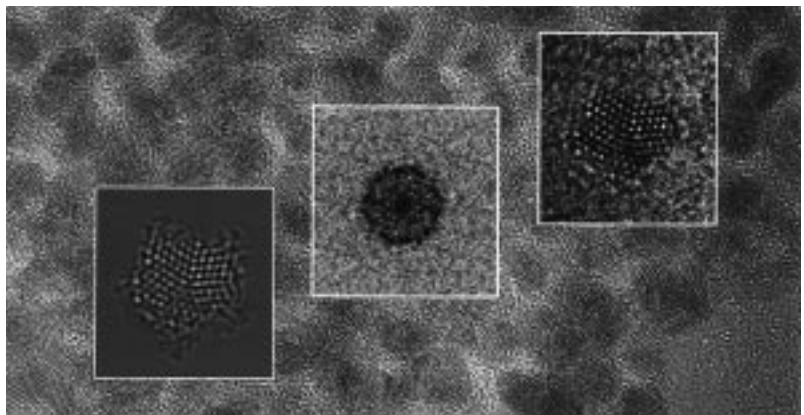


Figure 3.6.2
High-resolution electron microscopy image of Pd₅₆₁ giant palladium clusters. Particle size : 3 nm.

Some examples of applications

High-resolution transmission electron microscopy can be applied for the analysis of many nanosystems. A few examples for materials science are given in figures 3.6.1-3.6.3. The method can also be applied to electronic (figure 3.6.4) and biological systems (section 4.6).

Figure 3.6.3

Image processing at work: direct image, Fourier transform and inverse Fourier transform for three (a, b, and c) individual nanosized Pd₅₆₁ giant palladium clusters.

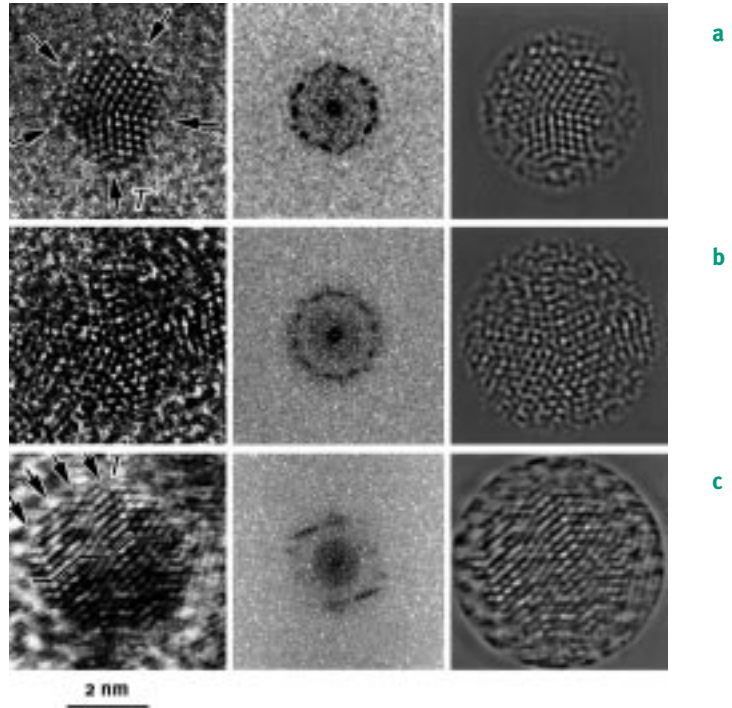
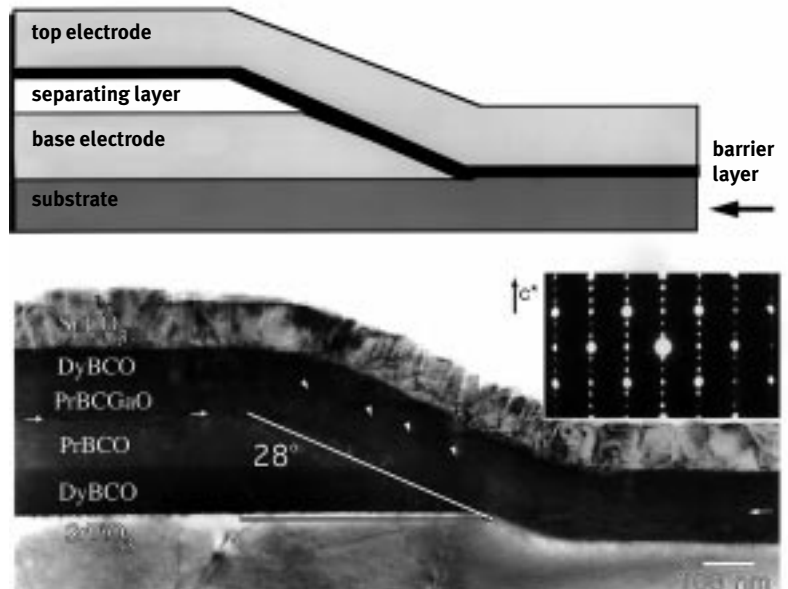


Figure 3.6.4

High-resolution electron microscopy for nanoelectronics: image of a Josephson junction made of a high-temperature superconducting material.



Prospects of high-resolution transmission electron microscopy

Modern transmission electron microscopy instruments can be readily used by materials scientists to study nanostructures. However, improvement in the ultimate resolution has become less and less spectacular. More importantly, the requirements for the sample thickness become more stringent to obtain this resolution and reach requirements that conflict with the size of the studied objects in the case of nanoparticles. We therefore believe that the evolution of electron microscopy will not be found in a further increase in the instrumental resolution but in the retrieval of structural detail by methods such as the focus variation method or holographic methods implemented by dedicated instruments [Amelinckx, 1997]. Further progress is also expected from the combination of current electron microscopy images with additional information that has, until recently, been considered optional. For instance, incoming electrons give rise not only to transmitted and elastically scattered electrons, but also to inelastically scattered electrons, backscattered electrons, electrons removed from the material, light and/or x-rays. All these outgoing waves carry information about the irradiated material. With a beam diameter (available in modern machines) in the nanometer range, this will provide structural, compositional, and electronic information about nanoscale structures. However, the quantitative interpretation of many of these 'secondary' effects is still not fully elaborated and improvements are still expected in this area.

Also other techniques could be combined with transmission electron microscopy. Particularly, now that STM or AFM have been further miniaturized, they qualify for being incorporated into the column of a transmission electron microscope. This should be done in such a way that combined surface and bulk measurements can be made on a single sample in vacuum. An experimental microscope combining different surface and bulk techniques with traditional electron microscopy is being built at Argonne National Laboratories in Chicago.

3.7 CONSOLIDATION: DEPOSITION OF NANOSTRUCTURED FILMS

*E.A. Meulenka*¹⁸

One of the most important aspects in processing nanoparticles is their consolidation. Pressing, molding etc. followed by sintering yield free-standing three-dimensional solid bodies. Particles can also be used for coatings.

The separation of the stages of production and consolidation allows developers complete freedom to independently optimize particle synthesis, particle surface chemistry and film formation. Hence the particles may have been prepared in either the liquid, solid or gas phase. Particles that can be purchased commercially can in principle be handled in the same way as other chemicals, i.e., stored and used when necessary. A general problem is that in dry form, many

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materials of great practical importance (ceramics, oxides) tend to form strongly bound aggregates. Complete de-agglomeration is essential for many purposes. If so, this can be achieved by processing in the liquid phase if the particles form a reasonably stable colloidal dispersion. However, meeting this requirement is often not a trivial matter (section 3.4).

This section deals with processing nanoparticles from the liquid phase for coatings. Possible routes to the formation of a thin film on an arbitrary substrate are discussed. Typical coating thicknesses lie between 1 monolayer (with a thickness depending on the particle size) and 10 to 50 μm .

The discussed techniques represent a mature field of science and are proven technologies for depositing many existing small particles. Intensive use of these techniques for consolidation of all kinds of nanoparticles into thin, uniform films is, therefore, expected. Optimal use will require a further understanding of processes that govern the film morphology since it has a direct influence on, for example, optical, electrical, thermal, and mechanical properties. This necessitates on the one hand an increased understanding of the stability and phase behavior of nanoparticles, and on the other hand the development of recipes for depositing particular coatings by fine-tuning of the process parameters. Both can be viewed as extensions of present-day science and technology.

CONVENTIONAL FILM DEPOSITION TECHNIQUES

Spin coating, dip coating, and solution casting

This family of deposition methods relies on dispensing a liquid on the substrate in the form of a continuous thin film [Brinker, 1990; Kistler, 1997]. After deposition, the solvent evaporates and a solid film remains. Film formation consists of three steps: deposition, drainage of liquid, and evaporation. Figure 3.7.1 on page 193 shows these steps for the spin-coating process. The substrate is spun at 100 to 1000 revolutions per minute and liquid is dispensed on the surface. The excess liquid is drained off by the centrifugal force. After a short time, thinning by drainage stops and evaporation takes over. In dip coating, the substrate is immersed and subsequently slowly drawn out of the liquid, covered by a thin film due to viscous drag. In solution casting, a viscous, concentrated particle solution is neatly deposited on the substrate, for example by pulling a special device called a 'Doctor blade' over the surface, and allowed to dry. A final heating step is often used to remove all solvent and promote adherence and mechanical strength.

Spin coating and dip coating produce films with a typical thickness of one monolayer of particles up to 10 μm . Thicker films can be obtained by repeated coating steps or by solution casting. Spin-coating and dip-coating can give very homogeneous films with less than 5% thickness variation over areas larger than 1000 cm^2 . Virtually defect-free thin films can be obtained in a clean-room

environment. The film thickness can be controlled within a few percent through the concentration of the particle solution, the substrate temperature, and the rotation rate of the spin-coater. However, this is found only for very flat and smooth surfaces. On corrugated substrates the presence of ‘hills’ and ‘valleys’ leads to ‘shadowing’ and very non-uniform coatings. Casting partly avoids these problems because much thicker films are applied. Reproducible results can be obtained for thicknesses over about 1 μm . Substrates with complicated three-dimensional shapes cannot be coated with any of these techniques.

The resulting film has a porous structure. The average pore volume, pore size, internal surface area and particle packing can be controlled in a precise manner. This is well-known in the field of sol-gel science for three-dimensional solid bodies. Factors that influence the morphology include the evaporation rate, particle aggregation rate, viscosity, and capillary pressure in the pores. Films with porosities ranging from 30 to 70% have been prepared by varying deposition conditions. Extensive knowledge is available for spin-coating, dip-coating, and solution-casting deposition of, amongst others, large colloidal particles, polymers (having nano-dimensions already), and sol-gel molecular precursors.

Spray deposition and aerosol deposition

Spray deposition and aerosol deposition are well-known techniques based on the impact on a substrate of small droplets of liquid containing a solid phase [Kistler, 1997]. Solvent evaporation transforms the layer into a solid film.

This kind of technique is used widely in numerous branches of manufacturing. The importance originates from deposition speed and versatility: large, complex objects can be coated. Layer thickness can be varied from several monolayers to more than 50 μm . No obstacles are foreseen that would prevent the development of these techniques for the use with nanoparticle systems.

Electrophoretic deposition

The deposition of particles by means of an electrical field (electrophoretic deposition, EPD) is a long-standing tradition [Sarkar, 1996]. It is also widely used for polymers and smaller molecules. Depending on the charge of the particles, they move to either the positive or the negative electrode. Under influence of an electrochemical reaction, the particles flocculate at the electrode surface and build up a layer. The electrode can be a large object or a very small feature. The automotive industry uses a process called electrophoretic painting to apply the primer coating for painting of automobiles. Selective coating of features as small as 100 nm does not pose particular problems either.

The film thickness can be varied from several monolayers to more than 20 μm . The film growth rate is approximately proportional to the local current. For insulating deposits, e.g. ceramic powders, the final film thickness is determined by the applied voltage. High local current density then leads to fast growth for a

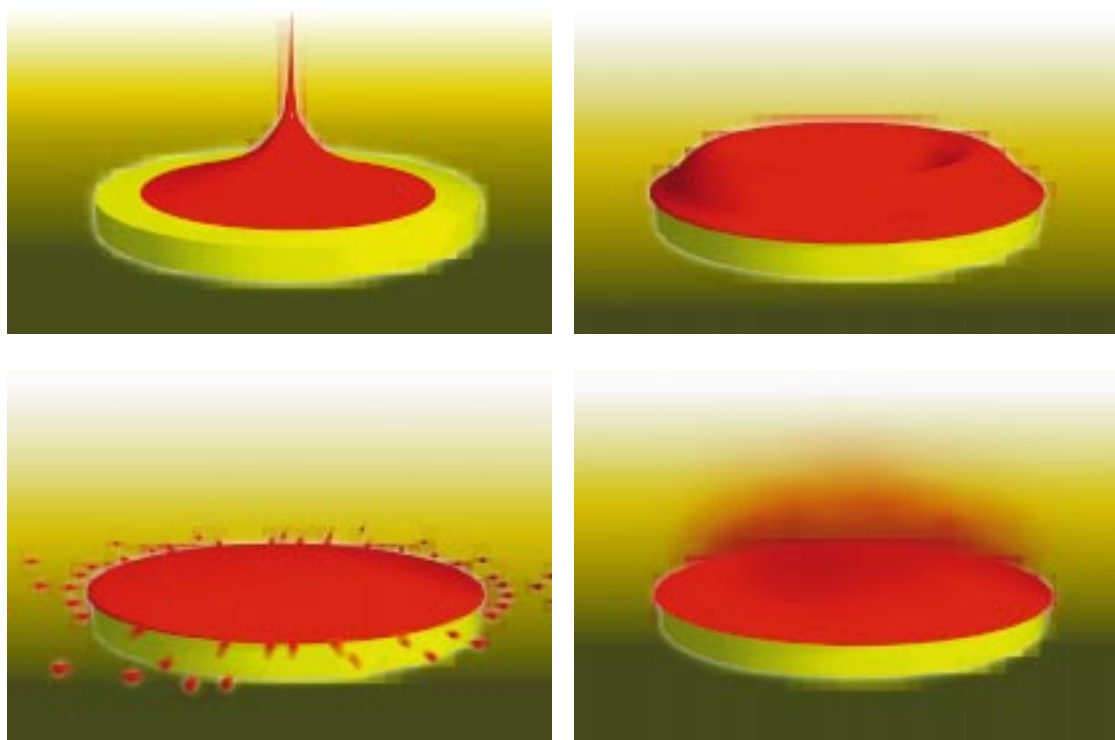


Figure 3.7.1

Stages of the spin-coating process: deposition (upper left), spin-up (upper right), spin-off (lower left) and solvent evaporation (lower left). Artist's impression after [Brinker, 1990]

short period of time. Other parts of the object may be coated at a slower rate, but for a longer time. Objects with extremely complex shapes, such as a pipe or an object with deep recesses, can be coated uniformly. This property is dubbed 'high throwing power'. Electrophoretic deposition is a proven technology which finds wide-scale and diverse application. The obvious limitation of electrophoretic deposition is the need for an electrically conducting substrate.

MOLECULAR NANOTECHNOLOGY FOR CONTROLLED MORPHOLOGIES

The level of control of individual particle surroundings is rather limited with the present deposition techniques. Particles are deposited simultaneously at high rates, and a driving force that could direct their assembly into a well-defined morphology is lacking. The rapidly emerging field of molecular nanotechnology, which studies bottom-up strategies such as self-assembly (sections 4.2-3), could provide an alternative to current deposition techniques. Although an extensive survey is presented in chapter 4, below some highlights concerning molecular nanotechnology and coatings consisting of nanoparticles are given. An analogy can be drawn with construction work. Most nanoparticles are shaped like irregularly shaped rocks of various sizes, such as the ones used in small walls in Cornwall and the Mediterranean to mark pasture borders. The

task now is to dump a load of rocks ('spin-coating' and 'solution casting') or to throw rocks one by one from a distance ('spraying') in a reproducible way such that they form a recognizable structure such as a wall, pile, blanket, or dike. Obviously, the use of bricks and mortar ('molecular nanotechnology') would greatly facilitate our effort, but these are not always at our disposal and manufacture may be too costly. We use them instead to build regular structures such as houses and pavements ('supramolecular structures', 'crystals', 'molecular wires'), which have much stricter specifications.

There is a huge effort in the scientific community to construct nanosized devices using a bottom-up strategy. In the context of construction work, the diversity of available bricks and mortar grows continuously and the masons are learning their craft. Almost without exception, this approach uses processing in the liquid phase. Molecular nanotechnology focuses on molecules as building blocks. Nanoparticles can be used for the same purpose. Layer-by-layer assembly can be achieved by means of so-called 'specific interactions' between alternate layers. Three-dimensional networks or nanocomposite materials can be prepared in a similar manner [Fendler, 1994]. The range of chemical and physical interactions exploited for such purposes rapidly expands.

Covalent bonding of particles to the substrate

One strategy uses covalent bonding of particles to the substrate. Gold particles attached to a surface by means of an organosulfur compound (thiol) represent a well-studied example. Sequential adsorption of thiols and gold particles can be used to build multilayers in a controlled way. In principle, such an approach can be used for any particle if suitable chemicals are at hand. This approach's scope can be expanded by using, for instance, polymerizable or multifunctional 'bridging' molecules. This last method has a well-developed chemistry, providing a range of headgroups and tail lengths, and variation of particle size. The technique is capable of producing three-dimensional networks of particles knotted together, and tailor-made coatings can be designed.

Electrostatic interactions

Another strategy makes use of electrostatic interactions. Figure 3.7.2 shows sequential adsorption of positively charged polyelectrolyte and negatively charged nanoparticles. A beautiful illustration of the possibilities is supplied by work on a light-emitting diode (LED) consisting of alternating layers of paraphenylene vinylene (PPV) and cadmium selenide (CdSe) nanocrystallites, sandwiched between two transparent electrodes [Colvin, 1994]. Upon application of a suitable driving voltage the cadmium selenide crystallites emit visible light.

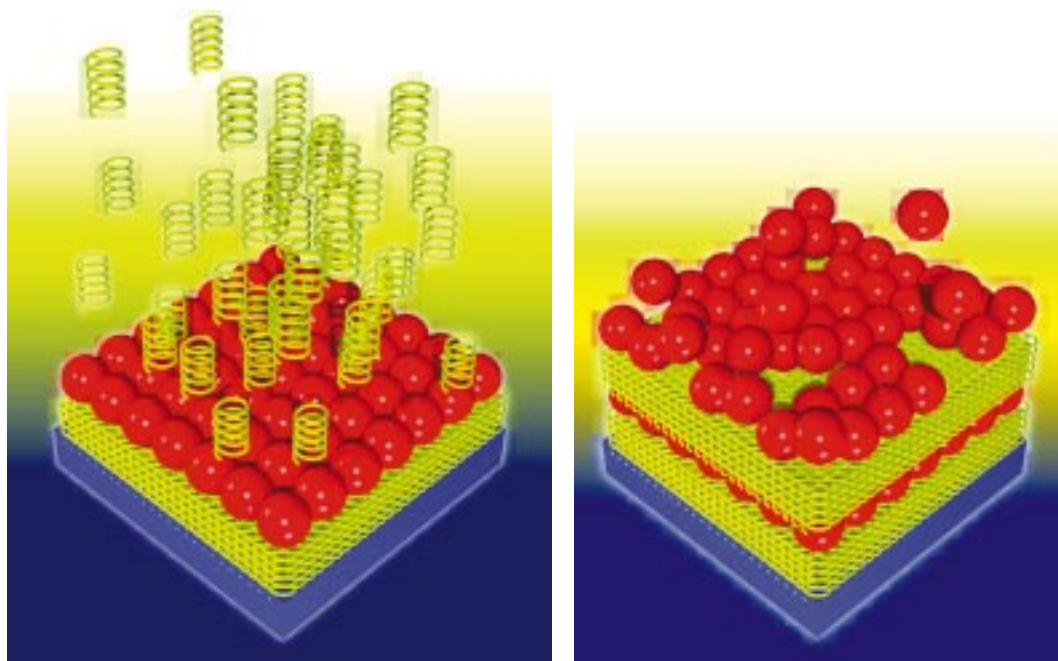


Figure 3.7.2

Schematic of the assembly of a nanostructured multilayer film formed by repeated sequential adsorption of (left) a positively charged polyelectrolyte layer of several nanometers thick (yellow) and (right) a monolayer of negatively charged cadmium sulfide (CdS) semiconductor nanoparticles (red) on a metal, glass or plastic substrate. Artist's impression after [Kotov, 1995]

Self-assembly

Self-assembly (section 4.2) of particles into an ordered three-dimensional lattice ('colloidal crystal') offers an exciting prospect for a whole new generation of materials. Opal is an example of such a system found in nature. Recently, it has been found that nanoparticles of equal size with a tendency to repel liquids (lyophobic) tend to crystallize when the solvent is slowly evaporated [Murray, 1995]. Such a superlattice structure (a lattice of particles instead of atoms) is expected to show entirely new collective electrical and optical phenomena. Parallel alignment of the individual particles has been demonstrated, showing that anisotropic properties can be anticipated. Epitaxial growth (continuing the substrate lattice structure) of such superlattices would exercise even finer control of layer structure. Preparation of multi-component colloidal crystals is also within reach. Langmuir-Blodgett films can be regarded as the two-dimensional analogues of such colloidal crystals. Such films represent a very-well-defined monolayer whose properties can be varied through the particle size and the attachment of bridging molecules.

Improved control over the process parameters

The first subsection described well-established techniques, widely used in manufacturing processes. Since they are not specific to nanoparticles, they are already being applied commercially for production of nanoparticle coatings. Trial and error is currently the major approach to optimization. The added value of nanoparticles can be exploited fully only when fine control of layer properties

can be mastered. The arrangement of nanoparticles in a solid film determines its quality. Its particular properties are not the sum of single-particle properties, but are due to the packing of particles and the interaction between them. It is expected that the next few years will witness marked improvements in our understanding and manipulation of factors that determine the morphology of nanoparticle coatings in general, as well as development of optimized coating recipes for specific applications. Because most of the deposition technologies discussed above require a lot of material, such a development will have a big impact on the demand for cheap processes for producing nanoparticles.

Molecular nanotechnology

During the past few years, the use of molecular nanotechnology using nanoparticles for coatings has been terra incognita for chemists and physicists alike. New possibilities have been explored and many new ideas will undoubtedly emerge in the coming years. The emphasis of the work is expected to shift from fabrication of layers to measuring layer properties. It is expected that devices with a high degree of sophistication can be manufactured.

The usefulness of the layer-by-layer approach seems limited to (very) thin films. The effort required for sequential deposition of many layers quickly outweighs the possible benefits. It is also questionable whether sharp interfaces and smooth layers can still be prepared for more than 20 multilayers. The advantages of this type of processing of nanoparticles should rather be sought in its unique ability to prepare well-defined, (very) thin layers with novel functional properties.

Controlled self-assembly into two- and three-dimensional networks and superlattices is particularly attractive because it combines relatively fast processing with control at the level of individual particle surroundings. Work will be aimed at a better understanding of the factors involved in the formation of regular structures. The influence of processing on the connection or communication (electrical, optical, thermal etc.) of nanoparticle layers with other parts of a device deserves considerable attention because of the existence of large interfacial areas in thin-film devices.

3.8 POLYMER CHEMISTRY

*F.P. Cuperus*¹⁹

There are major parts of front-line science and technology that border on nanotechnology. Polymer chemistry is one example. First of all, polymers have nanometer dimensions. Their structure can be well-defined on a near-molecular or molecular level, which is especially useful for high-added-value applications. With the progress of polymer chemistry, more complex molecular architectures are becoming possible, such as the use of different monomers in the chain, the attachment of end groups and side chains ('grafting') with specific interactions, and the synthesis of star-like polymers and semi-spherical dendrites (section 4.7). In many cases it is possible to produce a polymeric material with a narrow chain length distribution. Polymers are also important in hybrid coatings (section 3.3). And finally, the morphology of a polymeric material can be controlled by tailoring the molecular structure and the interactions between the molecules.

Tailor-made biopolymers

With the help of biosynthesis²⁰, some biopolymers can be made very specifically. Examples are the synthesis of silk, DNA and RNA. For this purpose nature uses specific interactions. These are selective interactions that occur between specific molecules or chemical groups, such as between an antigen and its corresponding antibody. Some biosynthesis reactions are realized using a so-called template construction (section 4.3 and 4.4). In principle this approach allows tailoring of the three-dimensional structure of each macromolecule in terms of molecular composition (the numbers of different atoms used), molecular mass (the total number of atoms), blocks lengths (including a controlled variation of the monomer units' occurrence from the beginning to the end of the polymer chain) and side chains for specific interactions. This allows one to tailor the molecular chain and thereby the properties of the materials.

For instance, the introduction of side chains of various length can influence the glass transition temperature. In this way, various more rubbery (i.e., with a glass transition far below 0°C) compounds can be synthesized. In addition to the glass temperature, the melting temperature of the rubbery polymer and the crystallinity decrease with the side chain length. The synthesis of 'silk-like proteins' (SLP) is another example. These polymers mimic natural silk protein [Cappello, 1994; Tirrell, 1994]. The structure of the synthesized polymer is not an exact copy, but a simplified imitation of natural silk protein [Lipkin, 1996]. The properties of the obtained synthetic silk are expected to approach those of natural silk to a great extent. With proper synthesis and processing methods, ultra-strong fibers can be produced, but elastic and rubbery materials can be made as well.

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20 The synthesis of complex molecules using enzymes and biological structures such as ribosomes and chromosomes, either within or without the cell

An important feature of biochemical synthesis is the possibility of synthesizing stereoregular polymers. These are polymers with a well-defined chain regularity with respect to the orientation of the side chains. This ‘molecular handedness’ is created by stereospecific sites on the biocatalyst surface. A technical problem in some of the available processes is the low yield.

Because of their superior control of the architecture of polymer chains, attempts to realize results better than nature still include a lot of modification using bacterial systems. The disadvantage clearly is the natural limitation of substrates the organisms are willing to accept.

Molecular filters

One can argue whether molecular filters belong to the area of nanotechnology. Still, the use specific semipermeable or binding materials for separation urges well-defined structures consisting of layers of less than 50 nm thick with pores nanometers or less in diameter. Nature’s examples are overwhelmingly accurate: the kidney is still a better separation device than man has ever made.

Recently, silica polymers were structured in very thin layers having very well-defined 0.5-nm pores [Dabadie, 1995; van Gemert; 1995], leading to a membrane with exceptional performance. Certain bacteria can produce structures with regular layers of thermally stable proteins with nanosized pores, that can be deposited on a support and used as a membrane that is very stable in a wide pH range and resistant to steam [Sara, 1996]. This gives an excellent example how a biological synthesis and successive physico-chemical step can yield interesting materials. However, most synthetic molecular filters are made from organic polymers. A polymer membrane can be made molecule-specific by applying a technique called molecular imprinting: the specific interaction with a target molecule is cultivated by making an imprint of the target molecule in the polymer matrix. However, up to now, the performance of most imprinted polymers is still poor.

Final remarks

Polymer chemistry can be used to tailor specific polymers and their structure. For instance, biosynthesis can be used for controlled synthesis of tailor-made materials that successfully mimic natural materials. Also, molecular imprinting can in principle be used to produce highly selective membranes. These techniques are still in the lab phase, but can be scaled up to an industrial scale.

3.9 HEALTH HAZARDS OF NANOPARTICLES

A. ten Wolde

The industry is producing nanostructured materials in increasing quantities. In the production phase of such products, human exposure to nanoparticles by inhalation may occur, for instance by diffusion in the upper airways [Cohen, 1995]. Also, if nanoparticles form an essential ingredient of the final product, such as sunburn lotion, they might penetrate the skin. This raises the following questions: do the nanoparticles used present any danger to our health? Could exposure lead to functional lung disease or cancer? And also: do nanopowders present any danger to our safety, in particular, can they explode?

Health hazards

The question of health hazards is all the more important since there is reason to believe that that nanoparticles may, depending on their chemical composition, be associated with the possibility of serious ill health [Pui, 1997; Jelinski, 1998]. Studies using rats have shown that several metal oxide nanoparticles show a highly increased inflammatory reaction compared to larger-sized particles of the same material [Oberdörster, 1992]. The precise mechanism behind this effect is not yet clear. It has been speculated that nanoparticles which are persistent in the lung may penetrate into the interstitium²¹ more easily and may penetrate through the cell membrane, thereby causing lung damage. Also, the large surface area per particle may result in an increased production of mediators that induce inflammation and cell proliferation. Similarly, exposure to fumes containing nanoparticles of the polymer polytetrafluoroethylene (PTFE) initiated severe inflammatory responses at low inhaled particle mass concentrations, suggesting oxidative injury [Johnston, 1996]. Nanosize Teflon[®] particles proved highly toxic [Oberdörster, 1995]. On the other hand, similar experiments with carbon black nanoparticles revealed little to moderate toxicity [Cassee²², private communication].

There is a lack of exposure data or epidemiology studies to either support or reject any further hypothesis concerning possible health effects. So far, most aerosol scientists have ignored nanoparticles occurring in our atmosphere. Even though nanoparticles dominate in numbers, they form a minor fraction compared to larger aerosols, both in terms of mass and surface area. From a practical standpoint, it is also important to recognize that nanoparticles quickly aggregate in the atmosphere to form larger particles [McClellan, 1997]. However, in recent years it has been recognized that particle numbers may yet be of toxicological importance. For instance, atmospheric nanoparticles were recognized as playing a potentially important role in the complex physical and chemical processes that occur above heavily polluted cities [Yacaman, 1997].

21 The interstitium includes a portion of the connective tissue of the blood vessels and air sacs and makes up the membrane where gas exchange (oxygen and carbon dioxide) takes place

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Safety

Do nanoparticle dust explosions form another potential risk? It is difficult to say. Research has shown that as dust becomes finer, the explosive power of dust increases due to the increasing surface/volume ratio. However, this increase levels off for particle sizes below 1 micron. This would suggest that nanopowders are not particularly dangerous [Lemkowitz²³, private communication]. On the other hand, no experimental verification of this hypothesis was found in the literature, and the American firm Argonide²⁴ claims that the energy and force of explosives can be enhanced by adding their nano-aluminum powder. If so, this could lead to important military applications.

Conclusion

Scientific evidence shows that several types of nanoparticles present serious health hazards for mice. More research is needed to investigate the effects of nanoparticles on humans. The risk of nanopowder explosions is unclear. The growing industry of nanostructured materials and other commercially interesting nanoparticle applications requires toxicological as well as epidemiological research on their effects, aimed at understanding and safety guidelines.

3.10 PRESENT AND FUTURE APPLICATIONS

A. *ten Wolde*

Present applications and market volumes [Rittner, 1997a]

Certain types of nanoparticles have been produced commercially since the early 1940s. Nanosized amorphous silica particles, especially, were developed as a substitute for ultrafine carbon black particles during World War II, and have since then found large-scale application in many everyday consumer products, ranging from nondairy coffee creamer to automobile tires. Since the 1970s, Japan has been producing various metal nanoparticles for magnetic recording tapes, while magnetic fluids containing suspended iron oxide nanoparticles entered the U.S. market. Bulk production of nanocrystalline powders and materials started in the 1980s, when various start-up companies were founded such as the Nanophase Technologies Corporation and Nanodyne, Inc. Since 1990, the interest in nanostructured materials has been ever increasing. Although much of the work in this field is still developmental, nanosized particles are currently incorporated into commercially available products such as abrasive polishing slurries, fire-retarding materials, magnetic fluids, sunscreens, sunburn lotions (based on UV-absorbing titanium dioxide nanoparticles), films protecting plastic against color degradation, optical cut-off filters, scratch-resistant plastic spectacles, rearview electrochromic mirrors on upscale automobiles [Geppert, 1997] and transparent wood stains. In addition to the metal particles, the

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nanostructured materials available in industrial quantities are ceramics, mainly oxides and carbides. Currently, over 50 companies are active in the U.S. alone. Available figures for the current and predicted overall market volumes for nanostructured materials in tables 3.10.1 (for the U.S.) and 3.10.2 (global) show a large and growing market.

Table 3.10.1

Existing and expected U.S. market volumes for nanostructured materials. Particles include dry powders and liquid dispersions. Source: Business Communications Company [Rittner, 1997a]

	\$ (millions)	
	1996	2001
particles	41	148
coatings	1	6
Total	42	154

Table 3.10.2

Existing and expected global market volumes for nanostructured materials. Data selectively taken from [BMBF, 1997]

	\$ (millions)	
	1996	2001
ceramics	5,912	8,811
coatings	2,103	8,811
pigments	568	1,137
solar cells	454	795
sunburn lotion	227	284
polymer composites	–	1,023
Total	9,266	20,864

A look at the website of the Nanophase Technologies Corporation (NTC)²⁵ shows that they have developed a process based on gas-phase condensation with improved fabrication rates and economies. This allows the company to produce approximately 100 tons of nanocrystalline materials per year at a few pennies per gram. It develops, produces and markets nanocrystalline materials for a wide range of commercial applications including electronic materials, catalysts, ceramic components, cosmetics and skin care, and pigments and coatings. NTC focuses on high-value opportunities with potential long-term customers who are industry leaders in these applications. It is the only non-electronics company to have published five or more nano-papers [Meyer, 1998].

Future applications

There are many opportunities for nanomaterials applications in the aerospace industry, the cutting tool industry, energy technologies, electronic engineering, and medical technology [Fecht, 1997]. A commercial report on these opportunities is available [Rittner, 1997b]. New products expected to appear on the market soon include nanostructured precision microdrills for circuit-board manufacture, nanocrystalline multilayer capacitors, and silica-based superstrong tires.

25 <http://www.nanophase.com/>

As discussed in section 3.1, most ‘advantages’ at the nanoscale for materials stem from either the small particle *size*, inducing quantum effects or changing classical properties such as the processing temperature, or from the large particle *surface area*, inducing bulk properties to become governed by surface properties. Some examples are given in table 3.10.3.

Table 3.10.3

Advantages of the nanoscale: some properties and future applications of nanostructured materials. After [Hofmann, 1997]

	property	future application
<i>particle size:</i>	single magnetic domain	magnetic recording
	smaller than wavelength of light	colored glass
	superfine agglomeration	molecular filters
	uniform mixture of components	new materials and coatings
	hindered propagation of lattice imperfections	strong and hard metals
	enhanced diffusional creep	ductile ceramics at elevated temperatures
<i>large surface area:</i>	specific	catalysis, sensors
	small heat capacity	heat-exchange materials
	dye-sensitized	solar cell

All these nanoscale phenomena can induce major changes in the mechanical, electrical, magnetic, optical, and chemical properties of nanoparticles and nanostructured materials. As a result, nanostructuring offers several general advantages for materials and coatings:

- ductile, better machinable (superplastic) ceramics at elevated temperatures
- ultrastrong, dense metals, ceramics and alloys
- nanocomposite materials with new or improved properties and a nanoscale morphology; ‘simply’ adding some volume percent of nanoparticles can improve products without the need of significant change of production process
- materials that can effectively be functionalized, e.g., using an light-absorbing dye
- materials with different electrical, magnetic, optical, or chemical properties (section 3.1)
- coatings that are mechanically strong, and/or resistant to wear and abrasion, flexible and impact-resistant, with a high thermal barrier, smooth, low-friction (self-lubricating), hydrophilic, corrosion-protective, with a high surface energy, absorbent, nanoporous, glossy, etc.

Exploitation of these new materials have enabled the demonstration of various possible applications. An extensive list of future applications is presented below [Kruis, 1998; INM, 1997; WTEC, 1998; Hofmann, 1997; Siegel, 1996;

Tolles, 1996]. Several of these are explained in comprehensible terms by the company Nanomat [Nanomat, 1997]. The list is by no means complete; the problem-oriented use of nanomaterials makes it hard to predict which specific applications will dominate the market. However, the sheer number of potential applications strengthens the conviction that nanomaterials face a bright future.

Energy technologies

- new types of solar cells, such as the Grätzel cell (section 1.2)
- window layers in solar cells from nanostructured semiconductors
- high energy density (rechargeable) batteries (section 3.2)
- smart windows based on the photochrome effect or electrical orientation [Geppert, 1997]
- better insulation materials
- nanostructured rocket fuel ignitors for longer-lasting satellites
- on-line repairable heat-exchangers in nuclear power plants [Fecht, 1997]
- nanocrystalline hydrogen storage materials
- magnetic refrigerators from superparamagnetic materials
- elimination of pollutants in power generation equipment

Automobile industry

- corrosion protection of an automobile's coach-work, stainless steel
- elimination of pollutants in catalytic converters
- electrical or hybrid cars using batteries based on nanostructured materials
- smart windows
- automobiles with greater fuel efficiency using nanostructured spark plugs and heat-resistant coatings for engine cylinders
- scratch-resistant top-coats of hybrid materials
- intrinsically simple couplings for automobile fabrication
- automobile engine performance sensor

Optics

- graded refractive index (GRIN) optics: special plastic lenses
- scratch-resistant plastic reading aids, lenses, visors, head lights and car windows
- anti-fogging coatings for spectacles and car windows
- cheap colored glass
- optical filters

Electronics: materials for the next-generation computer chips

- single-electron tunneling transistors using nanoparticles as quantum dots
- efficient electrical contacts for semiconductor devices
- electrically conducting nanoceramics

- conducting electrodes for photoconductors and solar cells
- capacitive materials for, e.g., dynamic random access memories (DRAM)
- magnetic memories based on materials with a high coercivity (section 3.2.3)
- magnetorestrictive materials, important for shielding components and devices
- soft magnetic alloys such as Finemet²⁶
- resistors and varistors (voltage-dependent resistors)
- high-temperature superconductors using nanoparticles for flux pinning
- liquid magnetic O-rings to seal off computer disk drives

Optoelectronics

- ‘nanophosphors’ for affordable high-definition television and flat panel displays
- electroluminescent nanocrystalline silicon, opening the way for optoelectronic chips and possibly a new type of color television [Palmer, 1997]
- efficient light-emitting diodes based on quantum dots with a voltage-controlled, tunable output color (section 2.3)
- plastic lasers using nanoparticles as an active scattering medium
- optical switches and fibers based on nonlinear behavior
- transparent conducting layers
- three-dimensional optical memories

High-sensitivity sensors

- gas sensors for NO_x, SO_x, CO, CO₂, CH₄ and aromatic hydrocarbons
- UV sensors and robust optical sensors based on nanostructured silicon carbide (SiC)
- smoke detectors
- ice detectors on aircraft wings

Catalysis

- photocatalytic air and water purifiers
- better activity, selectivity and lifetime in chemical transformations and fuel cells
- precursors for a new type of catalyst (Cortex-catalysts)
- stereoselective catalysis using chiral modifiers on the surface of metal nanoparticles

Medical

- longer-lasting medical implants of biocompatible nanostructured ceramics and carbides
- coatings for medical applications [Fecht, 1997]

²⁶ <http://inaba.nrim.go.jp/apfim/finemet.html>

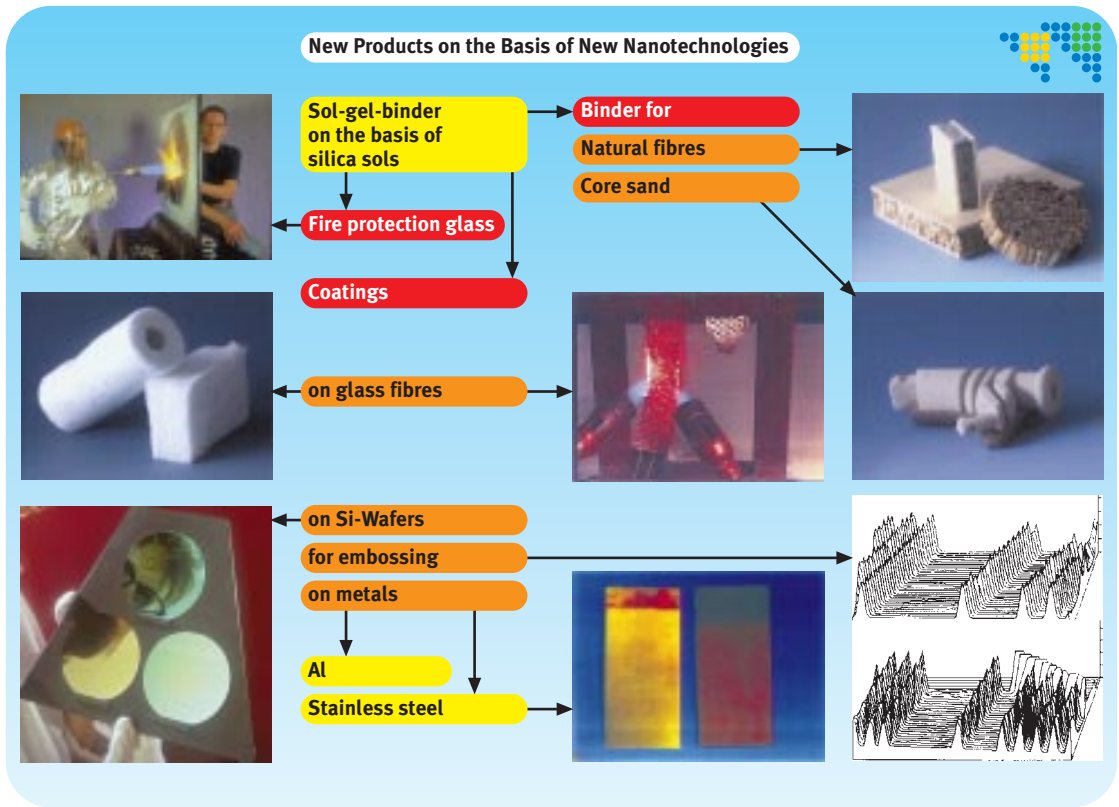


Figure 3.10.1

New products on the basis of nanotechnology. Courtesy of H. Schmidt, Institut für Neue Materialien (INM), Saarbrücken, Germany

Various other applications

- tougher and harder cutting tools, especially based on nanocrystalline carbides
- high performance parts for the aerospace and the building industry
- gas-tight and dense metals
- fire protection coatings
- 20-nm-thin foil for food packaging
- thermoelectric materials (used for thermocouples)
- ceramic membranes for energy-efficient separation methods (for uranium, milk, malt beer etc.)
- ‘self-lubricating’ coatings based on diamond-like nanocomposites, to be used on sliding parts in the automotive, chemical, pharmaceutical, or biomedical industry [Neerincx, 1997]
- easy-to-clean surfaces, for instance anti-graffiti coatings for trains, glass walls and brick walls
- strong plastic floors
- binder for natural fibers and core sand
- ferrofluids for mechanical vibration damping in stepper motors, magnetic muscles, dirt absorbers in waste separation facilities
- molecular filters
- fast-burning metal powders for the military

Hard coatings technology

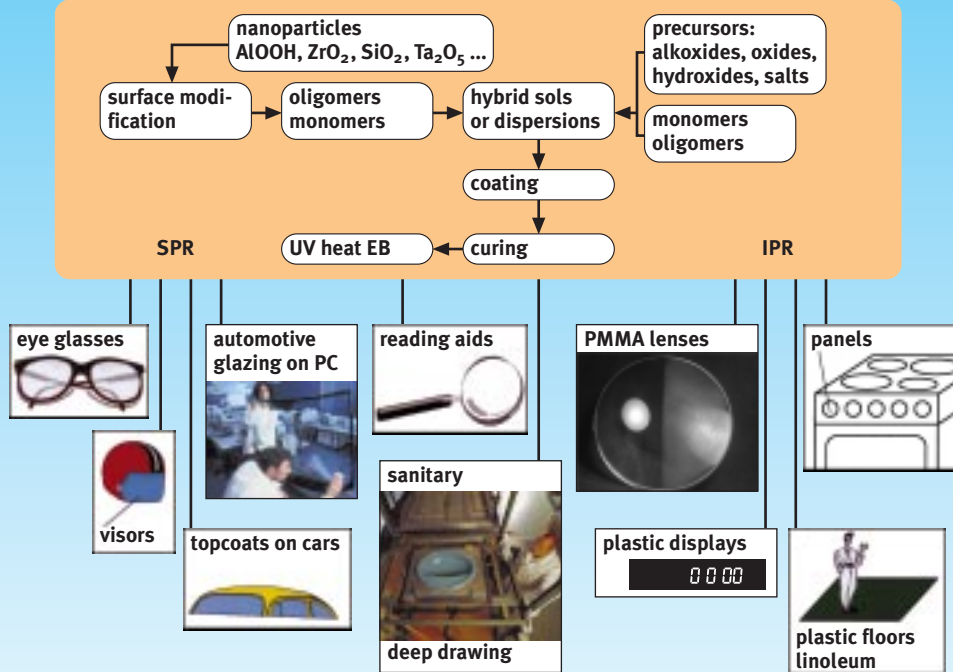


Figure 3.10.2

New products on the basis of hard nanostructured coatings technology.

Courtesy of H. Schmidt, Institut für Neue Materialien (INM), Saarbrücken, Germany

Promising research

Some research has not yet led to an actual demonstration, but might lead to interesting applications on a longer term:

- medical applications based on superparamagnetic nanocomposites: diagnostics, cancer treatment, drug carriers
- manufacturing of nanocomposite microparts and multilayers using inkjet and laser technology [Notenboom, 1997]
- projectiles penetrating hardened targets and armored vehicles (kinetic energy penetrators)
- longer-lasting, wear- and erosion-resistant railguns
- high-power rare earth magnets for quieter submarines, automobile alternators, land-based power generators, motors for ships, ultrasensitive analytical instruments, and magnetic resonance imaging (MRI) in medical diagnostics
- catalysts-by-design. It should be possible in the near future to relate the efficiency of catalysts to properties on the level of atoms and clusters. This could enable the industry to replace the current development process of (mainly) trial and error by one of rational design, which will hopefully lead to considerable advances.
- energy-level-tailored structures. The possibility of tuning the electronic energy level structures of clusters by varying their volume should lead to

novel and unexpected electronic properties such as tunable optical and dielectric properties.

- magnetic nanoparticles with functional organic coatings
- more selective synthesis using methods from (bio)organic chemistry
- self-assembly (sections 3.7, 4.2 and 4.3)

Some of the applications listed are illustrated in figures 3.10.1 (page 205) and 3.10.2. Many could become commercially available in the next 5 to 15 years (appendix 2). Wide-scale application of functional nanostructures in new (opto)electronic devices depends upon the developments in nanoelectronics, and is not expected in the coming decade.

3.11 OPPORTUNITIES AND CHALLENGES

J. Schoonman and A. ten Wolde²⁷

The nanoscale offers many opportunities for materials and devices with new properties due to surface enhancement and quantum effects. New technological developments in synthesis, consolidation, processing and characterization have enabled the production of nanoparticles and nanostructured materials that vary greatly in origin, composition, production method, properties and price. It is hard to predict which of them will play a role in products based on nanotechnology. Still, inorganic and hybrid materials are likely to play an important role, while biological systems will be used as examples for synthesizing nanoparticles. Meanwhile, it is important to realize that many aspects of nanoparticles in liquids have been (and are being) studied in colloid science; this area of nanotechnology is therefore likely to meet similar limitations. The main challenges along the path to new commercially viable products can be summarized as:

- *synthesis*: reproducible, scaleable production of nanoparticles with a uniform size
- *processing and handling*: controlled deposition; chemical stability; safety and health issues; induce the direct combination of synthesis, processing and product fabrication
- *characterization*: nanoscale-resolution microscopes are essential tools for rational design
- *rational design*: understanding nanoparticle formation and the critical role of surfaces, interfaces and defects; process control; developing process models; establishing process/product relationships; optimization of the whole cycle of synthesis-processing-product performance
- *economics*: cost-efficiency and intensive, focused marketing

²⁷ based on input from other members of the task force for this chapter

Near-term opportunities of nanomaterials lie in functional nanomaterials. Potential product areas are: tougher and harder cutting tools, high performance parts for the aerospace and the building industry, energy technologies, the automobile industry, optical and catalytic applications, and sensors. Indeed, materials and coatings with improved mechanical properties form a big opportunity. Examples are the superplasticity of ceramics during processing and the improved hardness of material end products. On a longer term, and dependent on the developments in the electronic industry, (opto)electronic applications of nanomaterials may find a big market in say, ten years from now. Interdisciplinary cooperation in research and development is important for the realization of scientific breakthroughs and for new products such as hybrid coatings or nanoelectronic devices. The ongoing separation of colloid physics and colloid chemistry is an undesired development (section 3.4). Because of the industrial interests, developing near-term commercially viable products is of vital importance for the development of the field.

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4

Molecular nanotechnology

4.1 INTRODUCTION

A. ten Wolde

What is molecular nanotechnology?

In general, the fabrication of nanostructures can be pursued in two ways. One is the top-down approach, starting with a bulk substrate in which small structures are created by lithographic and layering techniques involving physics and/or chemistry (chapter 2). The other is the bottom-up approach, where (identical) macro- or supramolecular structures are synthesized from atomic or molecular building blocks: ‘every atom or molecule in its place’. The latter is called molecular nanotechnology. Bottom-up indicates that some form of synthesis is involved, either chemical, mechanical (mechanosynthesis), or biological (biosynthesis). As a result of the requirement for atomic/molecular positioning, applications of molecular nanotechnology depend on the properties of *individual* atoms/molecules. Examples are molecular electronic devices or molecular machines. Many areas of physics and chemistry do not fulfill this requirement for fine positioning. Most techniques discussed in chapters 2 and 3 lead to the fabrication of nanosized structures without controlling the positions of individual atoms and molecules.

The nanostructured materials discussed in chapter 3 are based on polydisperse nanoparticles, polydisperse macromolecules or more or less randomly interpenetrating networks, and their properties depend on the *average* properties of their constituents. Similarly, monodispersity (particles of equal size) is hard to accomplish in polymer chemistry, which is therefore not treated as such in this chapter. An exception is made for the case of dendrimers, because they can be used for applications that depend on the shape of the individual macromolecules, especially drug-delivery.

However, the field of molecular nanotechnology is expected to expand. Some authors have already stated that synthesis methods that do control these positions provide new ways to control the properties of the product. Also, some of the bottom-up nanofabrication techniques using scanning probes treated in section 2.2.4 have atomic precision. The example of atomic manipulation mentioned and section 5.2 is, in fact, a beautiful example of molecular nanotechnology using the physical approach.

Nanobiosciences

The relationship between biology and molecular nanotechnology is a tricky one. In fact, many areas of biotechnology fulfill the requirements of molecular nanotechnology, but most biotechnologists don't consider themselves nanotechnologists. However, it is increasingly recognized that both biotechnological methods and the study of biological structures (structural biology) can be highly relevant to molecular nanotechnology. This new field is sometimes indicated as 'bio-nanotechnology' or 'nanobiosciences'. It describes a field of biological research with a clear interdisciplinary component. For instance, the emerging field of physical biology, which aims for a detailed (molecular) understanding of intra- and intercellular processes, is an example of nanobioscience. The physical phenomenon of tensegrity – an architectural system in which structures stabilize themselves by balancing the counteracting forces of compression and tension – forms the basis for the stability of the cytoskeleton of a living cell. A cross-over from chemistry to biology is *de novo* protein design: “the best way to understand the molecular machinery of life, is to build some yourself”, according to chemist William DeGrado from DuPont-Merck [Langreth, 1995]. Other examples are work aimed at bio-electronic devices, molecular motors and the understanding of photosynthesis. There is also increasing interest in molecular nanotechnology from researchers working on food technology, because molecular self-assembly, molecular recognition and biocatalysts are becoming increasingly important there as well.¹

About this chapter

One of the promises of molecular nanotechnology is the fabrication of a molecular machine, a nanostructure that performs specific operations on other atoms or molecules. One operation could be assembling another nanostructure; such a – hypothetical! – molecular machine is called an assembler. If an assembler could reproduce itself, it could be considered as a virus. Nature has developed interesting functioning examples of molecular machines such as viruses, ribosomes and molecular motors. Modification of natural nanostructures, using recombinant DNA technology for instance, can help in developing nanotechnology through a better understanding of how nanostructures function. This might lead to the development of, for instance, a bio-organic solar cell. 'Biomimetics'

¹ Several researchers from Wageningen, The Netherlands have actively participated in this study project.

is a term often used for this approach of ‘mimicking nature’. Note that evolution has produced impressive results, but that improvements as well as surprising new results are expected from bio- and nanotechnology. This chapter will discuss several fabrication routes for as well as natural examples of molecular nanotechnology:

- organic chemical and biochemical synthesis, including self-assembly (sections 4.2-5, 4.7-9, 4.14);
- investigation and modification of natural nanostructures (sections 4.6, 4.11-13);
- mechanosynthesis, the placement and connection of individual atoms, is briefly discussed in section 4.10.

The chapter is organized from simple to complex nanostructures. After opening with examples from organic chemistry, it gradually turns to more complex structures and concludes with DNA constructs. As in all science, computer simulations can provide very useful insights into the properties and behavior of nanosystems that are beyond the reach of contemporary experiments (section 4.10). The relevance of experimentally proven nanostructures for possible future applications will be discussed as well, especially in sections 4.7, 4.9, 4.12 and 4.15. The overview presents techniques from very different disciplines in chemistry, biology and physics. The fact that they are treated together in this chapter expresses the expectation that they will become more intertwined as molecular nanotechnology progresses.

4.2 SYNTHESIS OF NANOSTRUCTURES BY SELF-ASSEMBLY

B.L. Feringa²

If nature is considered as the ultimate example of how to construct nanosize molecular systems one cannot escape the fascinating way by which the biological machinery relies on self-organization, self-assembly and self-replication. One well-studied example is the assembly of the tobacco mosaic virus. In its assembled form, the virus is 300-nm long and has a width of 18 nm. It consists of about 2000 identical protein molecules forming a coating around an RNA molecule of about 6400 nucleotides (RNA is genetic material normally serving for the transcription of information from the DNA to the protein synthesizing machinery of cells). It can be assembled and de-assembled *in vitro*. This implies that all the components of the system contain all the information necessary to form a structural aggregate. The amount of information is surprisingly small. A remarkable feature of the assembly process is that the virus is constructed from sub-assemblies.

Large and extremely complex natural products have challenged the synthetic

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chemist for many decades and the tremendous progress in this field has cumulated recently in the total synthesis of nanosize multifunctional natural products such as vitamin B₁₂, palytoxin and brevetoxin (potent toxins produced by a coral and an algae, respectively). The construction of unnatural materials with nanoscale dimensions is limited only by the imagination of the synthetic chemist. Key problems in fabricating nanostructures are the design of efficient assembly processes with perfect control over molecular size and geometry. Also the synthesis of monodisperse systems is often a major challenge. Important tasks are also the introduction of appropriate functionalities to control molecular and supramolecular properties and to incorporate these in such a way that one can access the functions in the nanoscale constructs, for instance enabling the communication with these functions at the molecular level. To achieve efficient synthesis of functional nanoscale systems, new construction methods will be required. It will be evident that complicated multistep synthesis is best avoided. An emerging new methodology includes covalent or non-covalent bond formation strategies using ‘preprogrammed’ molecules. In this chapter two major approaches will briefly be outlined: covalent assembly (also called the ‘molecular construction kit’ approach) and self-assembly.

Covalent assembly

The use of molecular building blocks for the construction of larger covalent assemblies implies that stereoelectronic information is preprogrammed in the molecular units. With the proper design a minimum of external instruction is required to construct structurally complex systems with well defined and rigid two- or three-dimensional architectures and precise positioning of functional groups. An example is the synthesis of a molecular tape by cycloaddition (figure 4.2.1).

Figure 4.2.1

Scheme of a molecular tape. Its construction is realized by simple domino-like sequential cycloadditions (addition to a carbon-carbon double bond in which a ring is generated) that are completely controlled by the stereoelectronic information preprogrammed in the bisdiene and the bisdienophile units.

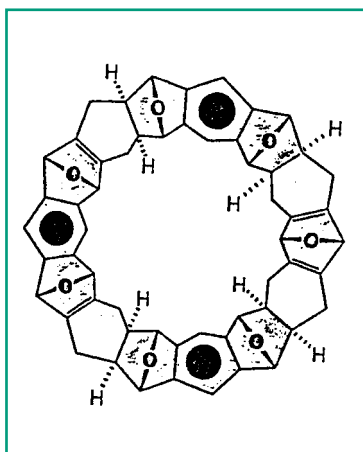
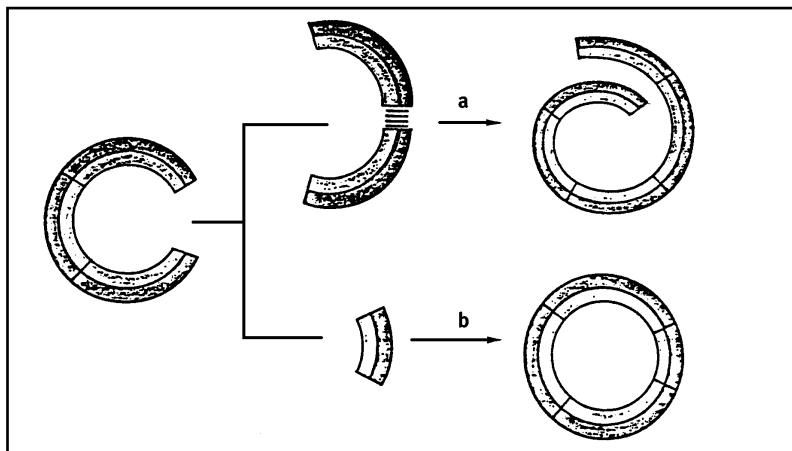


Figure 4.2.2

Schematic representation of the construction principle of molecular spirals (a) and belts (b) by a sequence of cycloaddition reactions of preprogrammed building blocks.



Similar sequences of repetitive cycloadditions (figure 4.2.2) led to the assembly of molecular belts, spirals and cages. The construction of kohnkene (about 1 nm in size, figure 4.2.3a) encapsulating benzene in the interior and of a container molecule (figure 4.2.3b) is also illustrative.

It should be noted that numerous other container-type molecules have been assembled in recent years that can encapsulate smaller functional guest molecules. These approaches pave the way to prepare a large variety of well-organized robust molecular constructs that ultimately could be used to assemble molecular machinery. The photoelectron transport systems constructed of five functional subunits (figure 4.2.4a), a photoswitchable molecular wire (figure 4.2.4b) and a molecular turnstile (figure 4.2.4c) are just a few examples of the numerous fascinating systems that can be readily constructed.

Figure 4.2.3

a Molecular belt constructed following the principle shown in figure 4.2.2; benzene is encapsulated.

b Molecular container compound.

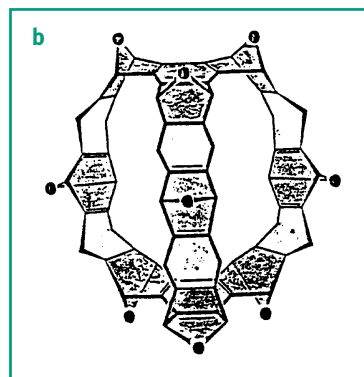
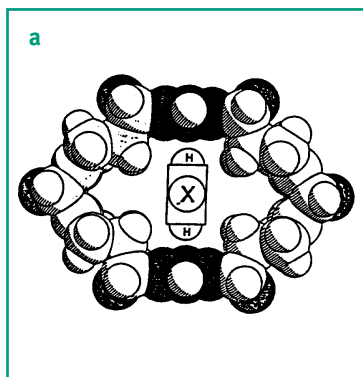
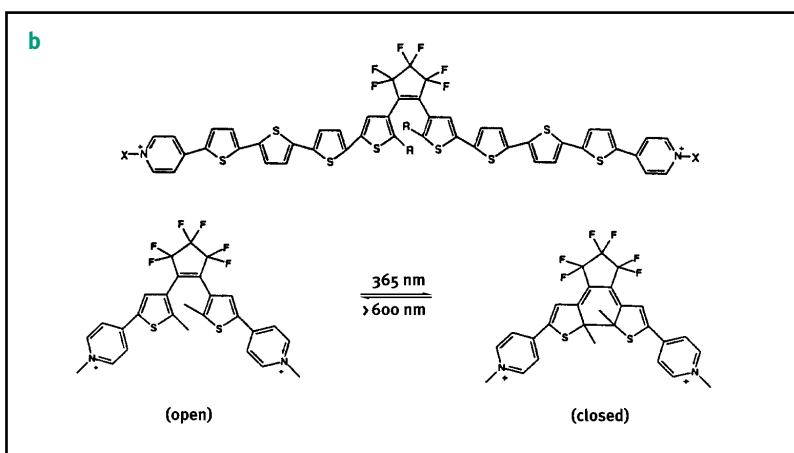
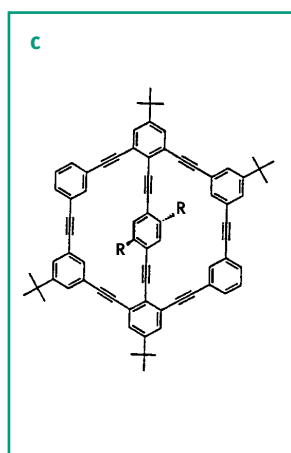
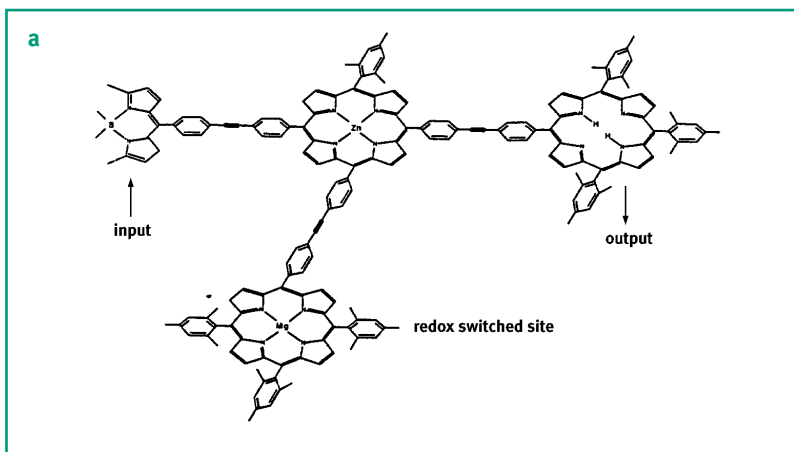


Figure 4.2.4.

a Electron transport system with five subunits containing porphyrins.

b Photoswitchable wire; the electronic communication between the outer parts is blocked in the open form.

c Molecular turnstile.

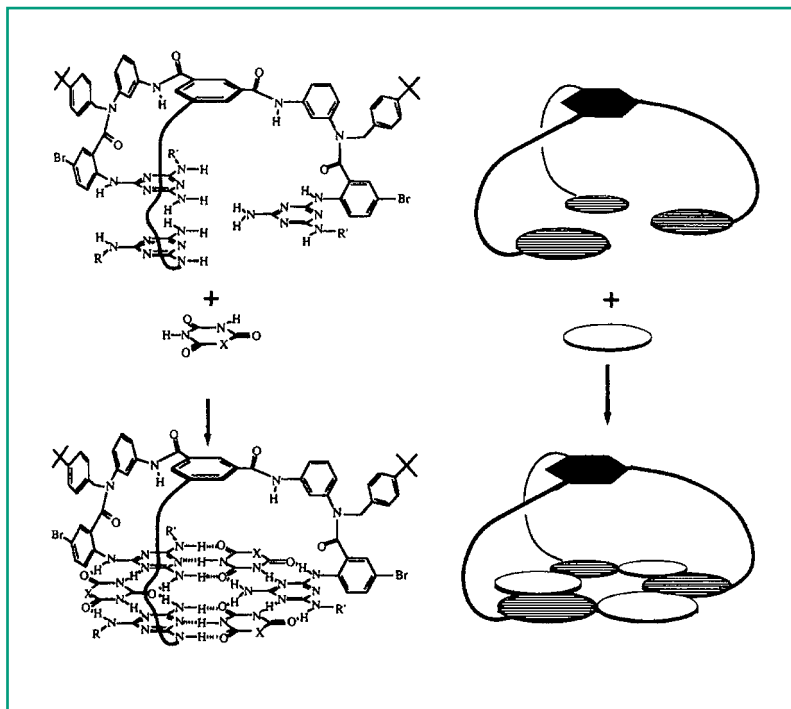


Self-assembly

Self-assembly has been defined as “the spontaneous association of molecules under equilibrium conditions into stable, structurally well-defined aggregates joined by non-covalent bonds” [Whitesides, 1991]. The synthesis of molecular structures that undergo self-assembly lies at the heart of future nanosystem design [Philp, 1996]. The information necessary for the organization process to occur must be embedded in the components and is expressed through selective molecular interactions. A distinction can be made between self-organization like the formation of crystals, vesicles or liquid crystalline phases and the much broader principle of self-assembly that governs the spontaneous generation of even very large systems capable executing complex functions. In approaches to generate molecules that are pre-programmed to undergo self-assembly the major intermolecular forces that can be exploited are ionic, hydrogen bond and coordinative interactions. Other interactions that can be beneficial to the assembly process are Van der Waals interactions and hydrophobic interactions. Technology for the generation of self-assembled structures has been developed

Figure 4.2.5

Molecular rosettes formed upon self-organization of melamine ($C_3H_6N_6$) derivatives

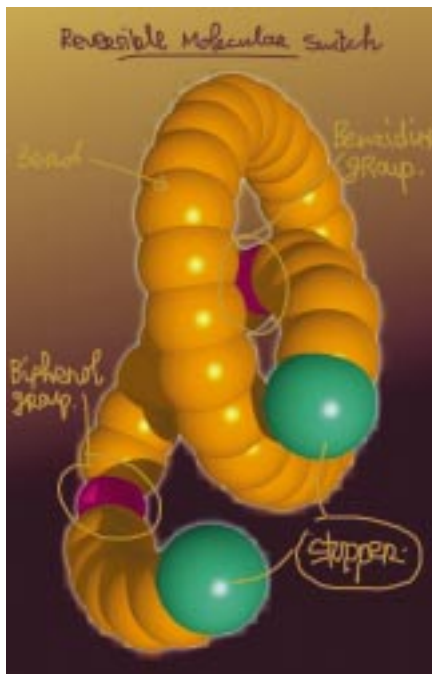


based on crystal engineering and patterning of monolayers (self-assembled monolayers (SAMs), section 2.2.2, see e.g. [Allara, 1996]). Organization through multiple hydrogen bonding and the formation of coordination complexes (section 4.3) has been investigated for the synthesis of large soluble ensembles. The lattices, tapes and three-dimensional structures shown in figure 4.2.5 are reminiscent of the self-organization of natural nanostructures such as DNA and proteins through multiple hydrogen bond formation. Highly efficient self-organization to stable systems with a large variety of architectures is possible due to the planar structure with multiple hydrogen bonding acceptor and donor functionalities. Further exploration of these principles allows the formation of numerous new materials with nanoscale structures including polymers, membranes, containers, wires, tapes, ladders and other equivalents of macroscopic constructs. That self-assembled structures can obtain micrometer dimensions is illustrated by the synthesis of porphyrin wheels with diameters up to $50\ \mu\text{m}$ [Schenning, 1996].

Fascinating examples of new strategies for making more complex systems, in which the assembly process allows also the design of specific functions, are the mechanically interlocked structures such as catenanes (interlocked rings) and rotaxanes including the molecular shuttle shown in figure 4.2.6. In these cases the self-organization is mainly governed by multiple electrostatic interactions.

Figure 4.2.6

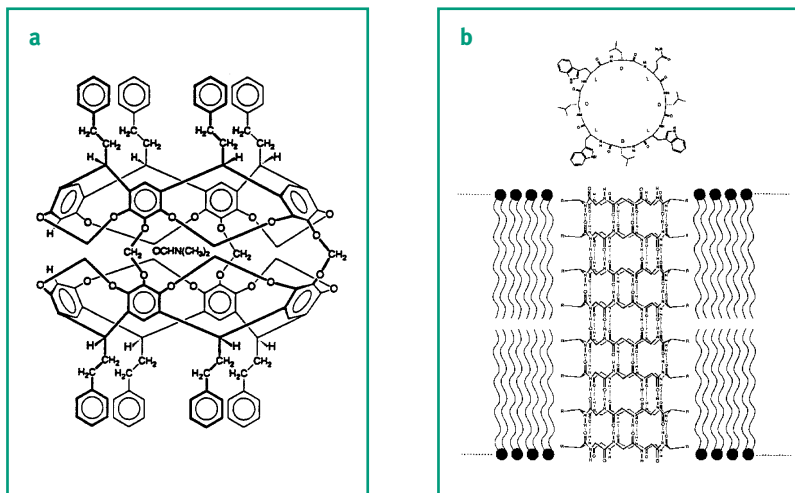
Artist's impression of a reversible molecular shuttle consisting of a rotaxane (a ring-shaped molecule around a linear molecule) that is formed by self-assembly. The ring slides along the chain until it encounters a functional group with a favorable specific interaction, where it finds a stable position. This switch is bistable and reversible; the two positions represent '1' and '0'. The ring is prevented from sliding off the chain by large end groups. Adapted from [López, 1996].



Recently a number of approaches have been studied in which several complementary groups are present in the molecular component with precise geometrical constraints. This is illustrated in the formation of molecular container molecules (figure 4.2.7a) suitable for acting as catalysts and nanosize tubes (figure 4.2.7b).

Figure 4.2.7

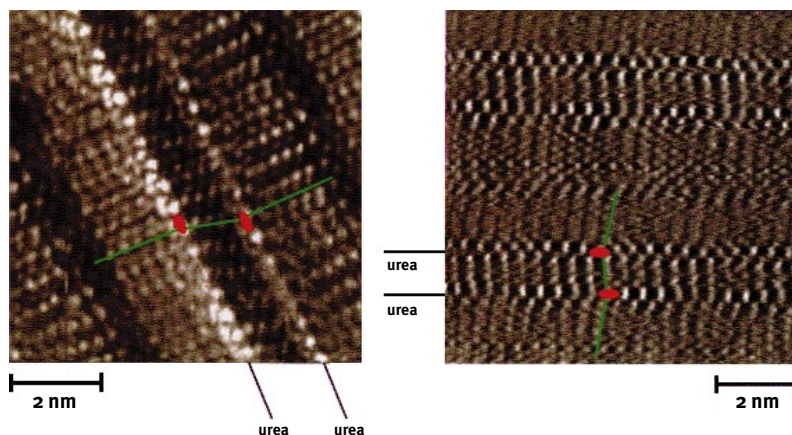
a Molecular container assembled through aggregation of two complementary parts.
b Cyclic aminoacid-based peptide-type tubes synthesized through self-assembly.



The organization process can readily be controlled by the shape of the organic building blocks and the number of ‘intelligent components’ included. The ease of structural modification and thus tuning of these features is a key advantage of nanofabrication based on organic molecules. The formation of nanosize tapes (figure 4.2.8) using bis-urea compounds is illustrative. Due to the ‘robust’ organization such systems are highly suitable to incorporate a diversity of functions. The external control of self-organized systems – the possibility to trigger

Figure 4.2.8.

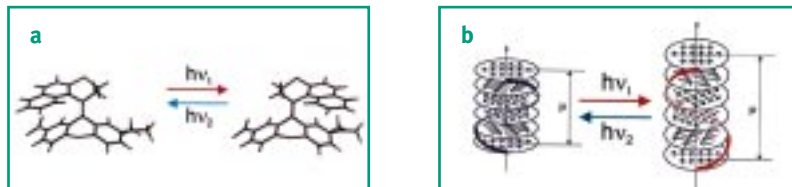
Scanning tunneling microscope (STM) image of molecular tape formed through self-organization of bis-urea ($\text{CO}(\text{NH}_2)_2$) compounds. The highly directional multiple hydrogen bonds control the linear organization while the shape of the molecule determines the aggregates that are formed.



changes in the assembly after its formation – is another major challenge. The architecture and properties of nanostructures can be reversibly modulated by external signals (mechanical, optical or electronic). In this way it is possible to ‘talk’ with the system at a molecular level. An example is seen in the reversible control of the organization – and thereby of the physical properties – of liquid crystalline (LC) matrices using chiral optical molecular switches as guests (figure 4.2.9).

Figure 4.2.9

Switching of liquid crystals for optical recording: A molecular switch (a) is incorporated as a guest within the host molecule of a liquid crystalline (LC) material (b). The organization and chirality of the liquid crystal phase is changed by photochemical control of the chirality of the switch.



An ultimate challenge in the construction of nanomaterials and devices will be the design of autoreplicating and autorepair systems. Successful approaches will not only require control of assembly but also precise control of molecular recognition, (auto)selection of components to be assembled and control of reactivity of several functional groups. The incorporation of such complex tasks in model systems (the first primitive systems have been reported recently) will set the stage to design nanoscale molecular machinery.

4.3 NANOSTRUCTURES THROUGH COORDINATION CHEMISTRY

*F.C.J.M. van Veggel*³

In this section a number of examples are described to highlight the large number and variety of nanostructures that can be generated with coordination chemistry, the chemistry of the coordinated bond. As already mentioned in section 3.2.3, a coordinative bond is formed by the electronic interaction of an organic or inorganic molecule (the ligand) with a metal (ion). An example is the coordination of pyridine via its lone pair of electrons on the nitrogen atom to a Cu^{2+} ion. Molecular nanotechnology is important for many applications because positional control allows for the fabrication of nanostructures with new functionalities. For instance, a redox-center located at a specific site inside a nanostructure might lead to a single-electron device. A redox center is an organic or inorganic species that can be oxidized or reduced by removing or adding electrons, respectively; the position at a specific site allows for the recovery of the original redox state.

So far, positional control has been often overlooked in chemical approaches towards nanoscale devices but it will probably become an important scientific research issue in the very near future. Self-assembly strategies are likely to become an important tool, and using coordination chemistry is one possible approach.

Coordination chemistry

The field of supramolecular chemistry has emerged from pioneering research on the 'recognition' of positively charged ions by encapsulating them as a guests in synthetic hosts [Pedersen, 1988; Lehn, 1995]. Over the last decades, the focus has gradually shifted from the covalent linkage of fragments with recognition sites to the use of non-covalent interactions like hydrogen and coordinative bonds. Coordination is often involved in the synthesis of hosts: the interaction with a metal ion induces the formation of the desired compound over others. This feature is often referred to as the template effect. If hosts are the desired products, the templating ion is normally removed but in nanostructures they are often an integral part of the targeted species. Simply put, the coordinative bonds keep the system together. For instance, a general phenomenon is that cage or capsule formation is only achieved when an appropriate guest is present [Patai, 1989]. Supramolecular chemists make more use of hydrogen bonds than of coordinative bonds to synthesize nanostructures [Conn, 1997]. However, coordination chemistry has two advantages compared to hydrogen bonds. First of all they are highly directional, especially when transition metals such as copper, silver and gold are involved. This is an advantage for the angular positioning of molecular building blocks. Secondly, the strength can be fine-tuned by changing the ligand.

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As Whitesides' definition of self-assembly (section 4.2) suggests, not all metals or metal ions can be used in self-assembly strategies. The prerequisite that the aggregates must be formed under equilibrium conditions only allows the use of *reversible* coordinative bonds.

Examples of nanostructures

Coordination chemistry has allowed the formation on the molecular level of interlocked rings and knots, double helices, grids, bicyclic systems, capsules and squares (figure 4.3.1-6). This had been a challenge for many years. A lot of the beauty in this field originates from the design of the polydentate ligands (i.e., ligands that have more than two reactive sites).

Figure 4.3.1

a Formation of an interlocked ring (a catenane) (reaction 1) and of a trefoil knot (reaction 2) by assembly of four phenanthroline molecules (lines) around one or two copper ions (bold dots), respectively.

b Chemical structure of intermediate structure in step 3 of reaction 1, showing the coordinated bonds of the phenanthroline groups (each containing two nitrogen atoms) with the copper ions. These bonds are broken again in step 4 as the ion is removed from the complex.

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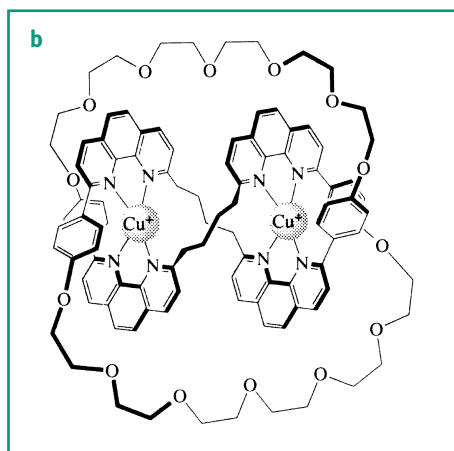
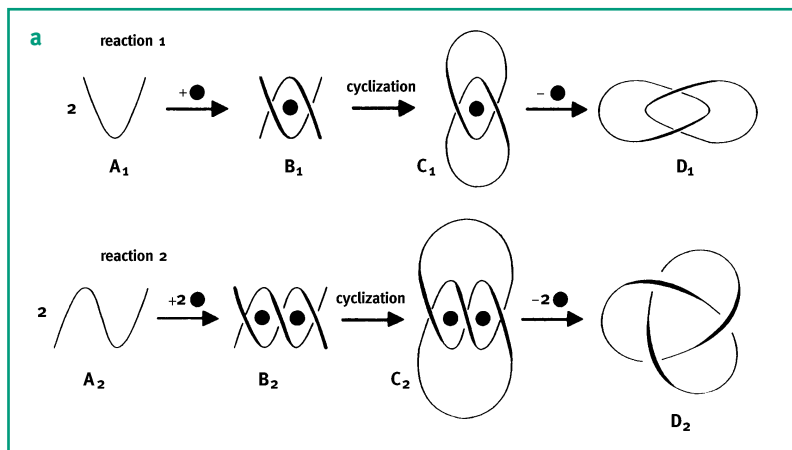
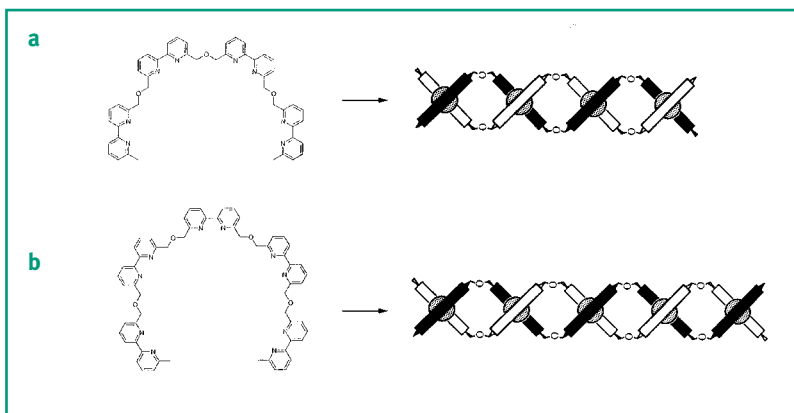


Figure 4.3.2

Tetra-bipyridine (a) and penta-bipyridine (b) molecules forming a supramolecular structure consisting of double helices of bipyridine units (white and black bars) around copper ions (grey circles) using the technique depicted in figure 4.3.1. Reprinted with permission from [Constable, 1996]. Copyright 1996 Elsevier Science.



The formation of double helices of bis-, tris- up to penta-bipyridines has been extensively studied [Constable, 1996]. The stable double helices are those where the two strands match. For the formation of the ones shown in figure 4.3.2, copper (Cu) ions are used as a template. Each copper ion can form coordinative bonds with bipyridine ligand molecules in the four directions of a tetrahedre. Together with the high flexibility of the bipyridine strands, this leads to the double helix. Geometry constraints have been imposed via the ligand and via the applied metal ions. The reversibility of the copper-bipyridine interaction is

Figure 4.3.3

Schematic (a) and molecular (b) representation of a 3×3 grid synthesized by the coordination of silver ions to rigid tris-bipyridines. Reprinted with permission from [Baxter, 1996]. Copyright 1996 Elsevier Science.

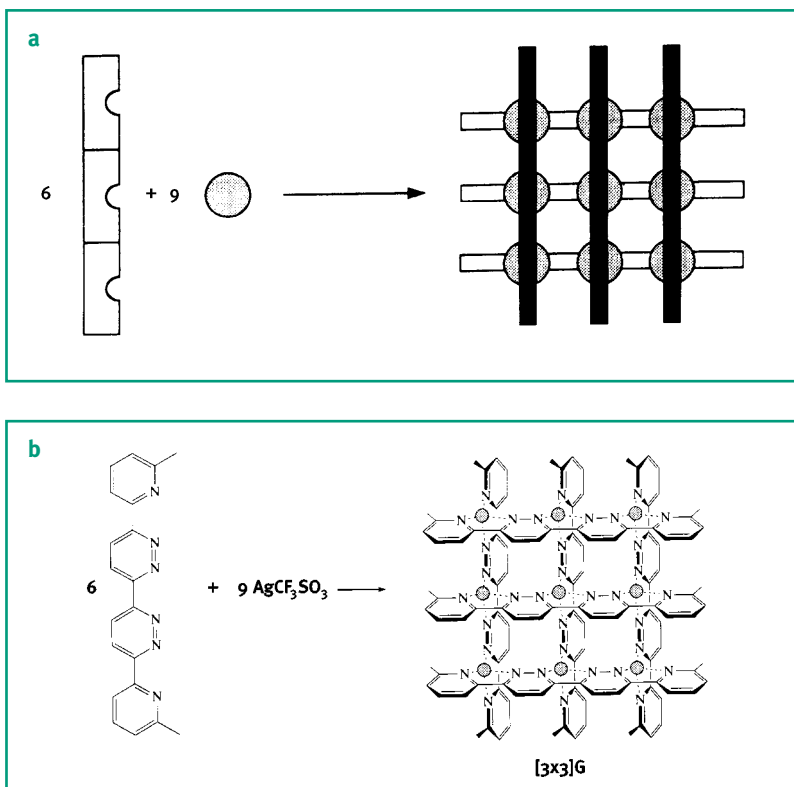


Figure 4.3.4

A bicyclic system formed by coordination of three palladium ions to two tripodant (three-armed) ligands. The precise configuration around the templating copper ions is controlled by the application of a specific ligand. Reprinted with permission from [Baxter, 1996]. Copyright 1996 Elsevier Science.

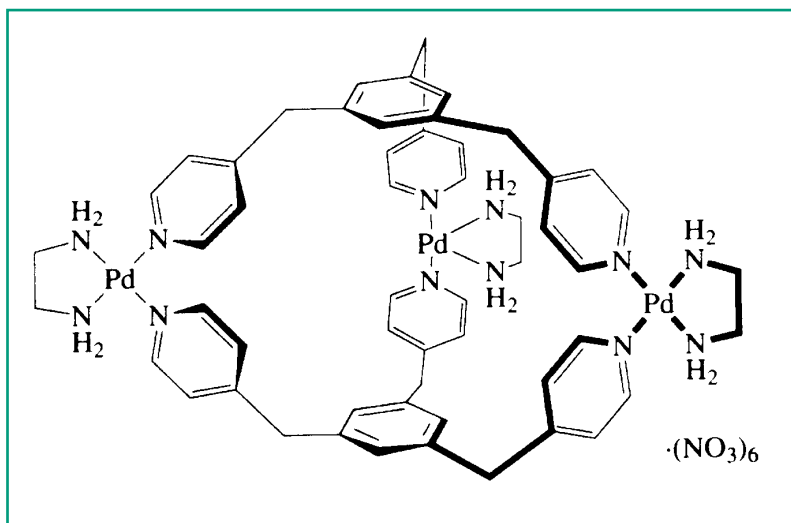


Figure 4.3.5 (left)

Molecular capsule. Cage compounds can be synthesized from tetracyano-cavitands and palladium ions. The building block is pre-organized in the sense that it is very rigid. The precise configuration of the cyano (C≡N) ligands is forced by the interaction of DPPP (1,3-bis(diphenylphosphorus)propane) with palladium. Reprinted with permission from [Jacopozi, 1997]. Copyright 1997 Wiley-VCH.

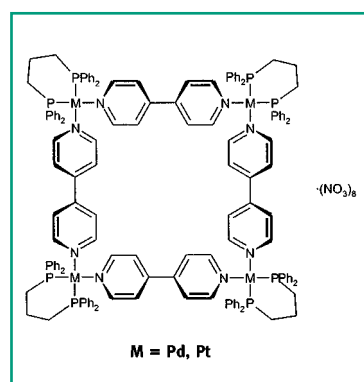
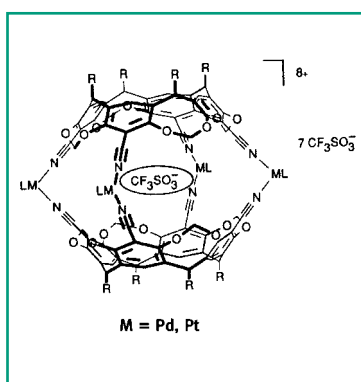


Figure 4.3.6 (right)

Molecular square. Reprinted with permission from [Fujita, 1996]. Copyright 1996 Elsevier Science.

crucial because it allows the system to correct itself and reach the thermodynamic controlled distribution. Several (pre-organized) helical ligands and also triple-strand and heteronuclear helices have been synthesized. The structure formed is determined by the flexibility of the ligands and the geometry the metal ions imposes. For instance, the assembly process can also lead to a grid as shown in figure 4.3.3. Structural variation of the ligand has led to a variety of grids of different dimensionality. Similarly, the combination of appropriate ligands has resulted in the formation of ladder type structures.

Palladium and platinum have a square planar coordination around them that has been extensively exploited [Fujita, 1996]. The orientation around the ions is induced by a rigid bidentate ligand that can only form bonds between two metal ions. In most cases, this leads to squares in high yields (figure 4.3.6). The squares can be very large. Large interlocking rings have also been reported.

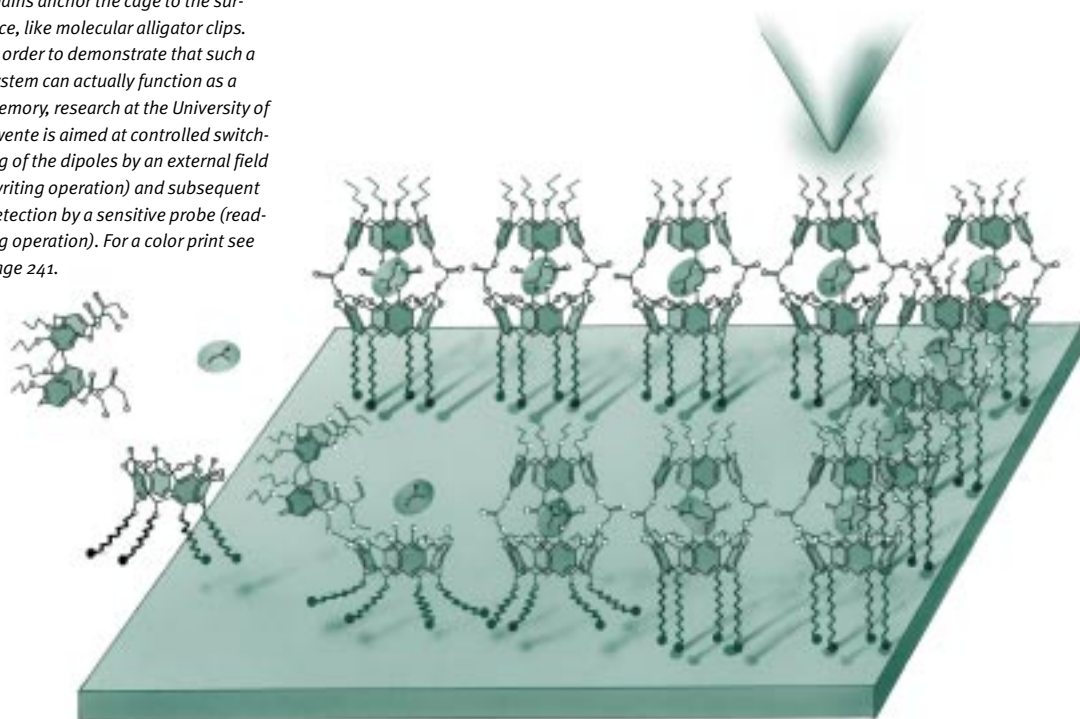
All of the above-mentioned structures are actually still quite small, i.e. a few nanometers. Dendrimers – also known as arborols, cascade, cauliflower, or starburst polymers – are attracting increasing attention because of their unique structures and properties [Zang, 1997]. They can have dimensions in the order of 5 to 10 nm. They are extensively discussed in section 4.7.

Conclusion

The examples given show that coordination chemistry can give rise to a large variety of nanostructures. Geometric constraints of the transition metal ion and the use of polydentate ligands play a key role in the ultimate structures. As mentioned in section 4.12, the most important challenge at the moment with regard to applications is the realization of ‘communication’ with such nanostructures. The function of a system as depicted in figure 4.3.7 as a molecular memory device has yet to be demonstrated. Position in space is, in the view of the author, an overlooked or ignored problem. Position is the confinement of a species in two or three dimensions, which is essential if, for instance, reading and writing has to be performed. One challenging way of controlling position is the assembly of assemblies, i.e., the construction of a supramolecular structure out of self-assembled molecules.

Figure 4.3.7

Artist's impression of a molecular memory constructed by self-assembly. On the left foreground, precursors form a molecular cage containing a small molecular dipole. Special groups at the bottom of the vertical chains anchor the cage to the surface, like molecular alligator clips. In order to demonstrate that such a system can actually function as a memory, research at the University of Twente is aimed at controlled switching of the dipoles by an external field (writing operation) and subsequent detection by a sensitive probe (reading operation). For a color print see page 241.



4.4 BIOMINERALIZATION AS A CONCEPT FOR MATERIALS ENGINEERING

*F. Lostak*⁴

Metals and minerals (naturally occurring substances of more or less definite chemical composition) play an essential role in all life forms. Living systems have learned to handle all kinds of amorphous and crystalline minerals in a very sophisticated way. Plants as well as animals have developed and optimized several mechanisms to synthesize and incorporate minerals for their own purposes. Commonly, metal ions from the environment are bonded into insoluble and/or inert minerals. These processes are generally known as biomineralization. Shells, teeth and bones are the most prominent structures containing biominerals based on calcium carbonate [Walsh, 1995]. The functioning of many types of processes and senses that are essential for the activity and development of organisms are based on minerals with very particular properties with regard to orientation, dimension and composition.

A common feature of minerals and metal particles produced by bio-organisms is that they have small, even nanosized, dimensions. The obvious reason for this is that they are produced inside a cell, which is typically of micron dimensions. Nanoscale particles allow for handling within the cell, extraction through membranes and easy incorporation in a matrix of macromolecules in order to form functional structures. An intriguing question is how organisms exert that remarkable control over minerals [Calvert, 1996a]. The formation of biominerals is highly regulated and responsive to the surrounding environment in a manner not achieved by conventional routes. Bio-organisms have developed a vast diversity of chemical strategies and techniques in the course of evolution that integrate processes of materials synthesis into much higher levels of organization and complexity than is possible with current materials technology.

Essential in the process of biomineralization are the macromolecules that act as templates at the cell membrane interfaces. They give rise to a controlled orientational growth of the minerals, which can, in turn, act as a template for new structures involving organic as well as inorganic materials [Weissbuch, 1991]. Mineralization and construction are thus integrated into a single process.

This is how, for instance, a sea shell grows: calcium carbonate mineralizes on protein substrates to form well-defined structures in one integrated process. The interaction at the organic-inorganic interface is the key to advanced materials synthesis [Rieke, 1989]. Biological concepts and mechanisms are being adapted into materials design and synthesis in two ways. First, bio-organisms are being used to synthesize biominerals in the form of crystallites with dimensions depending on the mineral formed and the environmental conditions [Lowenstam, 1981]. For instance, bacterial systems employed for cleaning up polluted soil or water (bioremediation) can be used to produce mineral powders or metal particles. Some systems provide crystalline or amorphous nanoscale

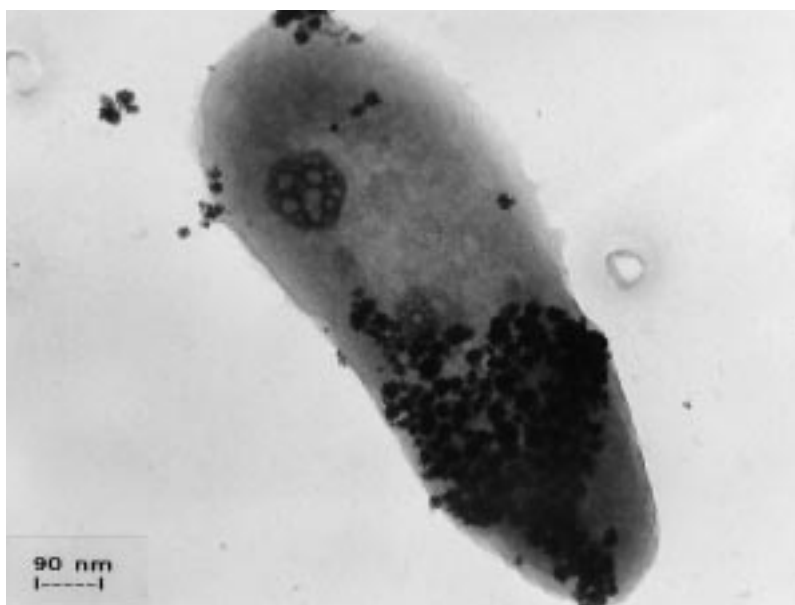
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particles from platinum (figure 4.4.1), cadmium sulfide (CdS), cadmium selenide (CdSe), selenium oxide (Se₃O₄) and iron oxide (Fe₃O₄, magnetite) [Gorby,1988; Frankel, 1991; Krüger, 1993]. The resulting materials are interesting because platinum nanoparticles may be used for catalysis, cadmium compounds for the semiconductor industry and selenium oxide for magnetic switches. While it is known that bacterial outer membranes serve as nucleation sites, the biological mechanisms responsible for the transport of the metal ions and the control over the nucleation process itself are far from understood and still under investigation.

The second use of biological concepts for materials synthesis is known as biomimetic materials synthesis. It is based on the sedimentation of inorganic material on organic substrates, which could be components of cells or even whole cells [Calvert, 1996b]. One can even use 'artificial' substrates for biomineralization, so that far more complex macromolecules could serve as a suitable substrate for mineralization. This is why the adaptation of the concepts of biomineralization is so important for future materials technology [Gür, 1996; Huer, 1992].

Figure 4.4.1

*Formation of crystalline platinum on the outside of the cell membrane of a *Pseudomonas Stutzeri* bacterium. The particles shown on this transmission electron microscope (TEM) image are actually clusters of smaller crystals a few nanometers in diameter.*



4.5 NANOSTRUCTURES FROM SURFACTANT MOLECULES

E.J.R. Sudhölter⁵

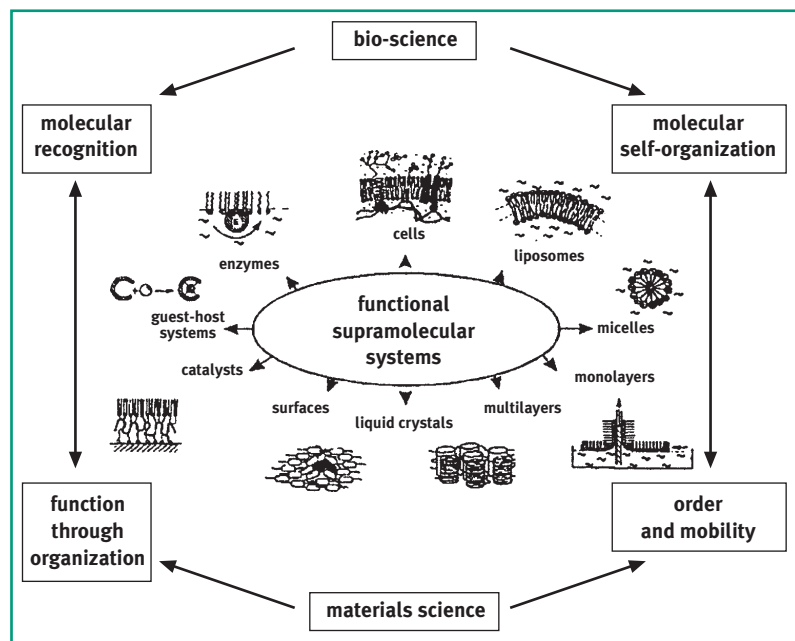
Introduction

A surfactant (surface active agent) is a compound that reduces the surface tension of its solvent, such as a detergent or soap dissolved in water. A surfactant molecule consists of a small hydrophilic headgroup and a hydrophobic tail. The aggregation properties of surfactant molecules in aqueous solution originate from the hydrophobic effect. This results in directing the apolar hydrocarbon part of the molecules to each other and forming a hydrophobic core while directing of the polar, hydrophilic headgroups towards the aqueous phase. In this way a variety of aggregate structures can be formed ranging from very small aggregates (dimers, trimers, etc.), micelles (spherical, rod- or disk-shaped), vesicle bilayer membranes (liposomes), monolayers, foams, and, in combination with other components, micro-emulsions and polymer-surfactant complexes. In figure 4.5.1 a schematic picture is presented to show the different aggregate morphologies. The aggregates obtained are generally polydisperse, that is, they have slightly different sizes and lack exact molecular positioning. They are treated in this chapter because they are supramolecular nanostructures with their shape and size controlled by specific molecular interactions.

Surfactant molecules can be synthetic or biological in origin. For instance, cholic acids and phospholipids are biosurfactants that form micelles and bilayer membranes, respectively. Such membranes separate the inside of living cells

Figure 4.5.1

Functional supramolecular structures form a bridge between bio-sciences and materials sciences. In materials science, (self) organization in two dimensions can lead to functional coatings (lower left), liquid-crystalline materials (middle left) or Langmuir-Blodgett layers. Self-organization in three dimensions can produce micelles or bilayer membranes (liposomes). The cell membrane consists of highly organized lipids as well, largely stabilized by proteins. The cell surface is covered with structures for molecular recognition, another important feature of supramolecular chemistry, of which enzymes and guest-host systems are examples. Reprinted with permission from [Ahlers, 1990]. Copyright 1990 Wiley-VCH.



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from the outside and form a matrix for membrane-bound enzymes and recognition sites. The research field of nanostructures derived from surfactant molecules is so broad that, in this contribution, only a snapshot of the author's view is given.

Increasing control

Several developments can be distinguished in supramolecular surfactant chemistry. For example, *functionalized surfactants* make it possible to influence the aggregation of surfactant molecules in new ways. Normally, the aggregation depends only on the surfactant concentration and the temperature. Above a certain critical aggregation concentration, micelles are formed. A certain (higher) concentration leads to the formation of liposomes. The introduction of functional groups in the surfactant molecules can make the aggregation sensitive to another external parameter. For instance, if light-sensitive units are introduced, illumination can isomerize two configurations (meaning that the surfactant molecules switch between these configurations). This might disrupt the formed micelles. Another interesting case is formed by diblock molecules such as $F(CF_2)_m-(CH_2)_n-H$. Since the fluorocarbon part does not mix with hydrocarbons, interesting aggregate structures are formed in hydrocarbon solvents. For the study of the aggregation of surfactant systems, several physical methods can be used including electron microscopy, scanning probe microscopy (chapter 5) and x-ray diffraction (section 4.11).

The *control of shape* is also increasing. Depending on the exact molecular structure of the constituent surfactant molecules, the shape of aggregates can vary from spherical to rod- and disk-shaped micelles or to vesicle bilayer membranes. The so-called surfactant parameter describing this relation is a powerful tool in the design of novel surfactant molecules [Israelachvili, 1992]. The shape of the aggregates determines the rheological properties of the solution and the soluble power of the aggregate.

Self-assembled surfactant systems are used as *templates* to control the formation and nanostructure of novel solid materials. For instance, semiconducting nanoparticles of lead sulfide (PbS) can be synthesized by exposing lead-containing Langmuir-Blodgett films to hydrogen sulfide (H_2S) gas [Zhu, 1992]. Layered silica-surfactant nanocomposite materials can be formed by polymerizing a silane in the presence of surfactants [Ogawa, 1997].

Another very promising area is the study of chemical and biological *recognition at interfaces* of microheterogeneous media like micelles, vesicles and monolayers. This is essentially a merging of the host-guest chemistry and surfactant chemistry. The recognition process can be very useful for the development of new separation technologies and sensors. Several spectroscopic methods are available for the study of molecular interactions in the system.

Applications

There are many applications for surfactants; only a few are mentioned here. Solubilisation is a very important property of surfactant molecules, leading to *detergents* and *cosmetic formulations*. Encapsulation by vesicles is used in the development of *drug delivery systems* (section 4.6). Surfactants also tune the *rheological properties* of solutions. For instance, viscoelastic properties can be obtained by introducing rod-shaped micelles. Surfactant molecules can act as a template in the formation of nanoparticles and nanocomposites. Finally, recognition in or at modified surfaces or interfaces can be very useful in the development of new separation technologies and sensing systems. The interested reader is referred to [Fletcher, 1996; Menger, 1995; Fennell Evans, 1994; Fuhrhop, 1994].

4.6 MEDICAL APPLICATION: DRUG AND DNA ENCAPSULATION

*P.M. Frederik*⁶

The developments in molecular biology during the last decades have enabled new therapeutic strategies for treating human diseases. By the growing insight in cellular recognition and transport mechanisms, site-directed delivery of compounds has become feasible. Also, interventions at the genomic level have become a therapeutic option because of the growing knowledge of gene defects and gene regulation. An approach of current interest is enveloping of drugs or DNA in a bilayer membrane capsule (liposome) to protect the contents from alterations by the patient's metabolism. Liposomes have an architecture similar to that of a virus particle as it appears in, for instance, an electron microscope image. The delivery system can be tailored to specific tasks – such as site-directed delivery – by adding specific molecules to the protective bilayer. A delivery system thus tailored resembles an addressed envelope containing a message read by only those cells that are addressed.

Drug-loaded liposomes

The encapsulation of the anti-cancer drug Doxorubicin into preformed liposomes utilizes a loading principle based on the formation of different conditions in the interior and exterior of liposomes [Ceh, 1997]. The liposomes are prepared in a solution that creates their internal environment. After this, the suspending medium is replaced by a solution containing the drug and heated so that the drug enters the liposome through the bilayer membrane, where it forms a liquid-crystalline precipitate. This loading principle is often referred to as 'black-hole loading' or 'gradient-loading' [Lasic, 1995a]. Efficient delivery of the 'deadly-cargo' of these liposomes to target cells depends on the composition of the enveloping membrane and the attachment of specific ligands to the outer

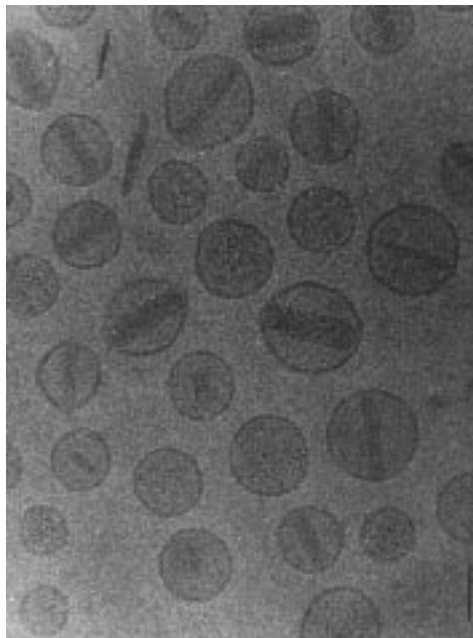
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leaflet of this bilayer. The architecture of the outer layer of the bilayer is of special concern [Lasic, 1995b]. The outer layer should protect the cargo when traveling through the body to its destination, so that the cargo does not interact with the blood or with the walls of a blood-vessel that it meets under way. Upon arrival at this destination, the particle should recognize the target site, adhere and destabilize ('unload') at this site. However, most liposomes are immediately neutralized by the immune system when injected into the bloodstream. A reduction of this uptake by the immune system is therefore a prerequisite for obtaining the prolonged circulation times needed for an efficient delivery system. Recently, the circulation time of liposomes was increased substantially by incorporating a lipid molecule in the bilayer that has a polyethylene glycol moiety coupled to its polar headgroup. This increase was caused by the steric repulsion provided by the polyethylene glycol group, that sticks out of the liposome and serves as barrier to unwanted uptake. These liposomes are referred to as Stealth® liposomes⁷.

In addition to steric repulsion, the polyethylene glycol group provides a site for coupling site-specific ligands. These ligands can be coupled to the polyethylene glycol-lipid molecules, which are subsequently incorporated in the outer leaflet of the enveloping bilayer of preformed drug-loaded liposomes. Such a strategy employing specific molecular interactions potentially allows tailoring of drug-loaded liposomes to the individual cancer type(s) of a patient (figure 4.6.1).

Figure 4.6.1

Micrograph of liposomes loaded with the anti-cancer drug Doxorubicin vitrified in suspension, taken at -170°C. The bar represents 50 nm. Doxil® specimen from Sequus, Menlo Park, CA.



⁷ 'Stealth' is a registered trademark of Sequus Pharmaceuticals, Menlo Park, CA, USA

Figure 4.6.2

Micrograph of DNA-loaded liposomes vitrified in suspension, taken at -170°C . The bar represents 100 nm. Reprinted with permission from [Smyth Templeton, 1997]. Copyright 1997 Macmillan Magazines Limited.

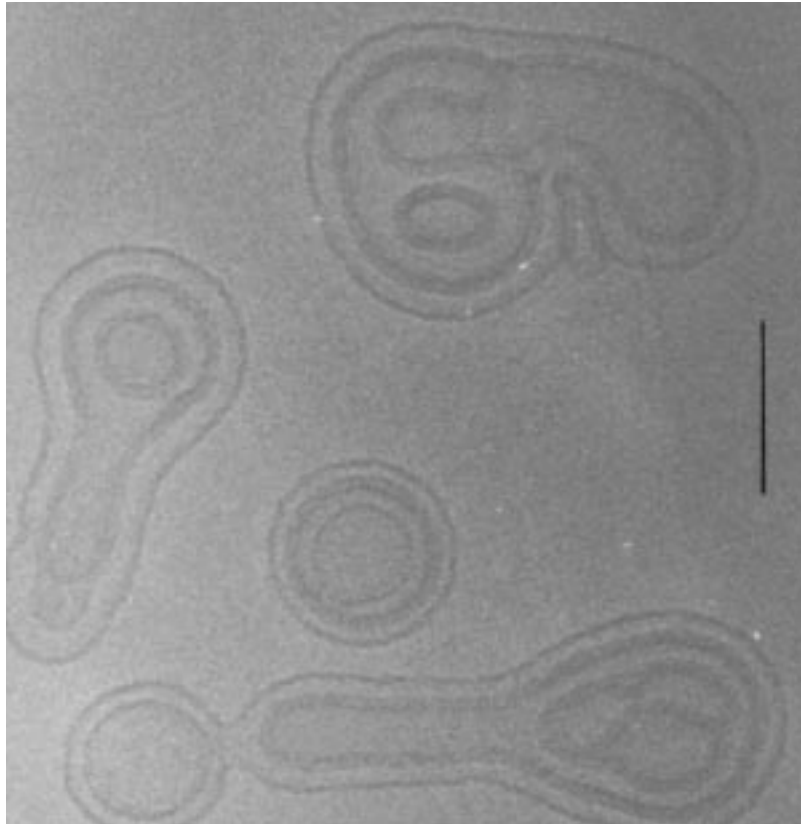
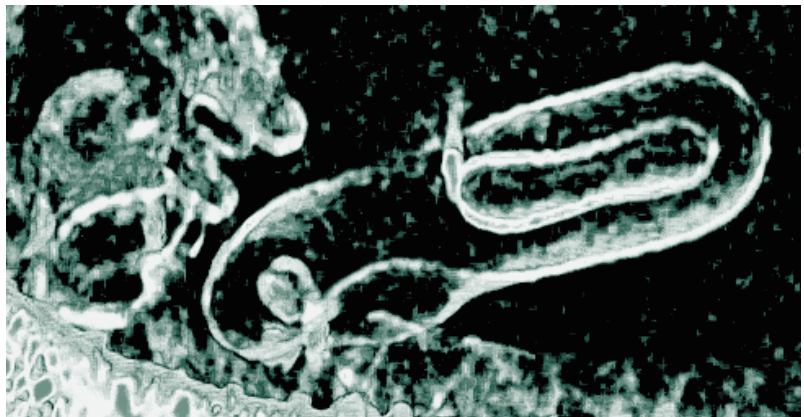


Figure 4.6.3

Tomography provides a three-dimensional reconstructed image of lipid/DNA complexes. For a color print see page 241.



The development of drug-loaded liposomes for therapeutic applications is currently at a stage of pre-clinical trials (site-directed delivery) and clinical trials (delivery through leaky liposomes) [Lasic, 1996]. The next generation of drug-loaded liposomes will in all likelihood contain further developments of proven principles, such as the tailoring of liposomes, combined with some new features, such as the controlled discharge of the contents by additional bilayer constituents.

DNA-loaded vesicles

Lipids can form complexes with DNA (figures 4.6.2-3). The complexes are typically the result of the interaction between negatively charged DNA with positively charged lipids. In contrast to drug-loaded liposomes, the development of lipid/DNA complexes is still in an experimental and pre-clinical phase. Applications mostly concern the alteration of the genome of a cell culture or a tissue culture after 'infection' with the lipid (transfection) and are less concerned with intact organisms. Commercial preparations of positively charged lipids usually produce (sub)micron-sized complexes when combined with negatively charged DNA. These complexes are efficient in transfecting cells in culture but they are rapidly cleared from the circulation when injected into the bloodstream of experimental animals. The quest has been for compact complexes, i.e. complexes with a high DNA content per volume. They should be small enough to prevent occlusion of capillaries, while still large enough that the DNA is protected by a lipid barrier [Lasic, 1997]. A highly efficient natural lipid/DNA complex for gene delivery was recently found in an intact animal [Smyth Templeton, 1997]. Cryogenic electron microscopy demonstrated that (condensed) DNA was encapsulated by a lipid bilayer membrane. This structural information explained the protection of DNA in the circulation and thus the delivery of undamaged DNA to those cells that have taken up the complexes. The efficiency *in vivo* of this gene delivery system was about two orders in magnitude better than reported thus far for any other lipid/ DNA complex. Targeting of these efficient complexes was achieved by coating with a liver-specific ligand.

Conclusion

Self-assembling structures are being developed for the efficient delivery of drugs and DNA into cells of the human body. Such structures contain elements that mimic biological membranes and the individual particles are some 10 to 100 nm in diameter. Cryogenic electron microscopy has played a crucial role in the investigation of the three-dimensional structure of these drug and DNA loaded vesicles that are based on the self-assembly of components into supramolecular structures. Further developments are expected in delivery systems when these systems are tuned to specific functions by the addition of specific DNA/RNA and proteins.

4.7 DENDRIMERS

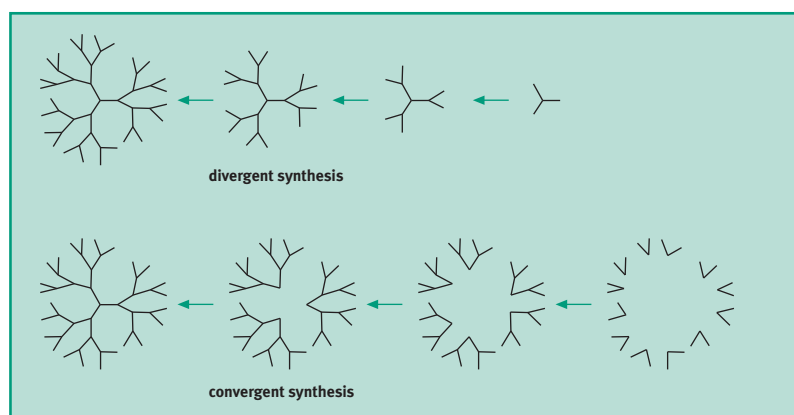
P.E. Froehling and E.M.M. de Brabander-van den Berg⁸

Introduction

A new type of synthetic macromolecules, called dendrimers, are characterized by a maximally branched structure of high regularity (figure 4.7.1). The word ‘dendrimer’ derives from the Greek word for tree, δένδρον. The scientific interest in synthesis and characterization of dendrimers (also called ‘dendritic molecules’ or ‘dendritic macromolecules’) originated around 1980. The literature on dendrimers has been expanding continuously, especially after 1990 when it became apparent that their special structure can lead to unique properties and potential applications. At present, about 120 academic and industrial laboratories throughout the world are involved in research on synthesis, characterization and application of dendrimers.

Figure 4.7.1

Divergent and convergent routes to synthesize a dendrimer of the third generation (the result of a three-step synthesis) with a trifunctional core (the core has three branches) and trifunctional branching points (three branches meet at each branching point).



The synthesis of dendrimers requires a step-wise approach to obtain the extremely regular structure. At this point it differs fundamentally from conventional polymerizations, which are either based on repeated addition of monomers to the growing chain (addition polymerization) or on the gradual, random combination of monomers, dimers etc. (condensation polymerization). Two synthetic strategies can be distinguished (figure 4.7.1). One is the divergent route, in which the dendrimer is built up from a central core. In a repetitive cycle layer after layer are added by bonding building blocks. The branches grow by consecutive additions of ‘generations’ of branches. In the convergent route complete wedges (also called dendrons) are synthesized first, starting from a branched starting molecule. In a final step, the wedges are coupled to a polyfunctional core. This approach has the advantages that the various products are more easily separated if reaction is incomplete and that in principle different wedges can be added to the same core. The divergent route has shown itself to be especially applicable for dendrimer synthesis on an industrial scale, whereas

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the convergent route can be used in the laboratory for the preparation of tailor-made dendrimers.

Theoretically, the result of both types of synthesis is a collection of identical macromolecules. In this respect, dendrimers resemble many naturally occurring polymers. In the divergent synthesis of higher generations, small variations in the molecular weight of the dendrimer molecules can occur due to the many chemical transformations that have to be carried out simultaneously, which can lead to side reactions. In this respect, the divergent route can be regarded as the 'polymer chemistry' approach since molecular weight variations are encountered in many synthetic polymerization routes. In contrast, convergent synthesis has the character of the step-wise or 'organic chemistry' approach. Only a few simultaneous reactions are carried out during the construction of the dendrimer, and they are often accompanied by intermediate purification steps. A great variety of chemical structures of dendrimers has been reported. Well-known dendrimers are Tomalia's poly(amidoamines), DSM's poly(propyleneimines) and Fréchet's poly(benzylphenylethers). At present, DSM is the only company producing dendrimers on a (pre)industrial scale. Most dendrimers are smaller than 5 nm (table 4.7.1 at the end of this section) and are constructed by using covalent bonds only [Newkome, 1996]. However, larger and more complicated dendrimers have been synthesized in the laboratory. Using a controlled assembly approach, dendrimer molecules up to generation 5 have been synthesized, with an identical size of approximately 10 nm. Functional groups like porphyrins have been introduced. Nanostructures with both hydrogen and coordinative bonds have also been realized. Spherical particles in the range of 50 to 200 nm have been obtained with a reasonably narrow size distribution using a special scheme in which the number of reaction sites is doubled in each generation [Huck, 1997].

Structure and properties

Characteristic of all dendrimers⁹ is the presence of many end groups and branching points. The number of end groups is determined by the number and functionality of the branching points. Many chemical and physical properties of dendrimers (e.g. aggregation state, reactivity, stability, solubility, toxicity) are directly related to the nature of the end groups, so that chemical modification of the end groups is often used to control the properties.

Compared to linear macromolecules, the shape of dendrimers is much more compact, and approximately spherical. Whether the end groups of the dendrimer are present exclusively on the outside of the sphere (forming a more or less closed shell in higher generations) or are distributed throughout the molecule (by backfolding of the branches) is a subject of ongoing discussion. In higher generations, the spherical shape becomes more pronounced. Size and molecular weight of dendrimers depend on the generation number and on the size of the building blocks. Some representative data are given in table 4.7.1.

⁹ For examples see http://www.wag.caltech.edu/gallery/gallery_dendrimer.html

For a given type of dendrimer the highest generation that can be synthesized without defects can be estimated. This maximum is limited by the branching functionality and the distance between the branching points, in other words by the compactness of the molecule. At a certain stage the surface of the dendrimer becomes so crowded that not all reactive groups are accessible and hence imperfect dendrimers are obtained. In the poly(amidoamines), which have six atoms between their branching points, the 11th generation is still obtainable, while the poly(propyleneimines) with three atoms between the branching points can be synthesized up to the sixth generation.

Between the branches, there is room for small guest molecules in the interior of the dendrimer molecule. Guests can be simple solvent molecules, but it has been proven that host-guest systems with, for example, controlled-release properties can be constructed by appropriate modification reactions.

Applications

The following examples show some potential applications of dendrimers.

Four of these are based on specific surface modifications, the other three on host-guest properties of dendrimers.

Electrically conducting dendrimers [Miller, 1997]

Poly(amidoamine) dendrimers were treated to obtain negatively charged radicals on the surface. The high conductivity of films of these materials was probably caused by the stacking of the aromatic rings.

Liquid-crystalline dendrimers [Lorenz, 1996]

A specific end group was attached via an 8-atom spacer to a carbon/silicon dendrimer. This material was liquid crystalline (a liquid phase with molecular ordering) from room temperature up to 130°C. The authors envisage an application of this material as a dopant for low-molecular-weight liquid crystals.

Dendrimers with catalytic activity [Knapen, 1994]

The end groups of carbosilane dendrimers were modified by adding ligand molecules. The ligands in their turn formed complexes with nickel and other metals. The resulting metal-carrying dendrimers were used as effective homogeneous catalysts in several reactions, after which the catalyst can easily be separated from the products, for instance in a membrane reactor system¹⁰.

Dendrimer as DNA carrier [Poxon, 1996]

Poly(amidoamine) dendrimers were able to form stable complexes with short nucleic acid molecules. Living cells absorbed the dendrimer-complexed nucleic acids much easier than uncomplexed material. This principle is applicable for gene therapy.

10 A membrane reactor system is a reaction system combining membranes and chemical reactions. Reaction and separation can occur either simultaneously or in separate zones.

Figure 3.1.1

An artist's impression of nanoparticle synthesis by condensation in the gas phase. See also on page 148.

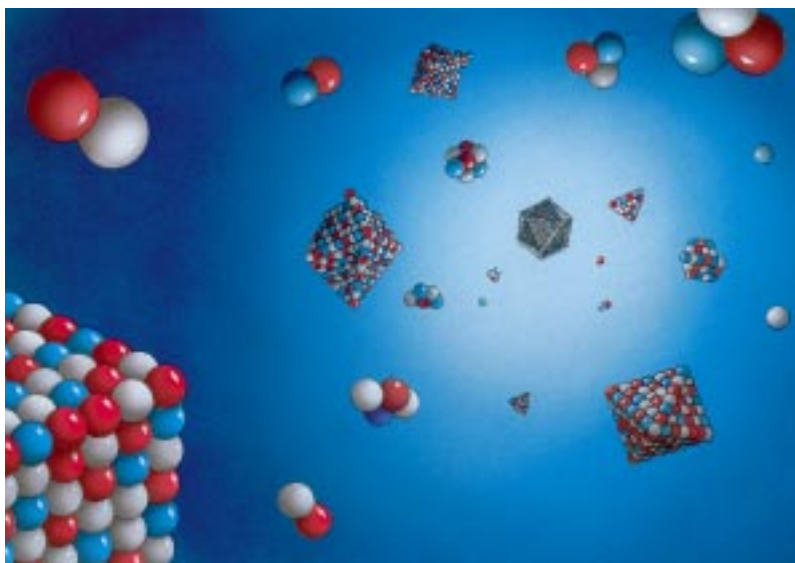


Figure 4.3.7

Artist's impression of a molecular memory constructed by self-assembly. On the left foreground, precursors form a molecular cage containing a small molecular dipole. Special groups at the bottom of the vertical chains anchor the cage to the surface, like molecular alligator clips. In order to demonstrate that such a system can actually function as a memory, research at the University of Twente is aimed at controlled switching of the dipoles by an external field (writing operation) and subsequent detection by a sensitive probe (reading operation). See also on page 229.

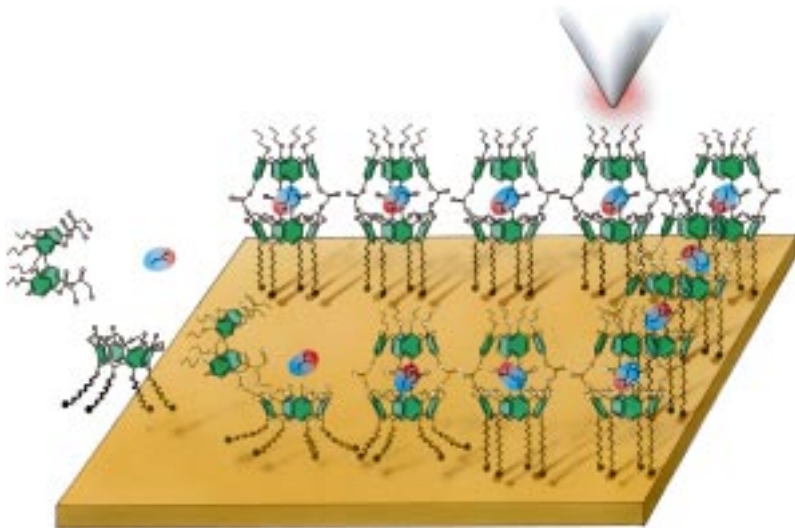


Figure 4.6.3

Tomography provides a three-dimensional reconstructed image of lipid/DNA complexes. See page 236-237.

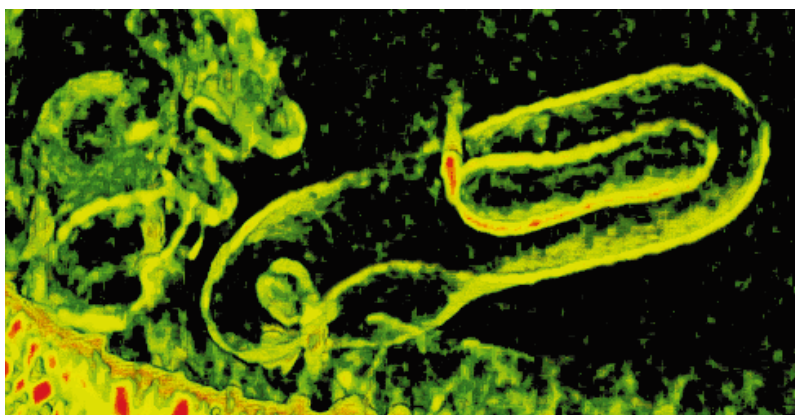


Figure 4.10.1

Top (left) and side (right) views of a Van der Waals sphere representation of an imaginary molecular bearing composed of interlocking graphite tubes generated with the Tube program [Merkle, 1991] and displayed using the program Quanta97. Unfilled chemical bonds of the graphite tubes have been capped with nitrogen (blue), sulfur (yellow) or hydrogen (white) atoms. Carbon and oxygen atoms are colored green and red, respectively. The inner tube has a diameter of 2.5 nm. It is intended to rotate within the outer tube by transforming chemical or radiational energy into mechanical work. See text on page 253 and further.

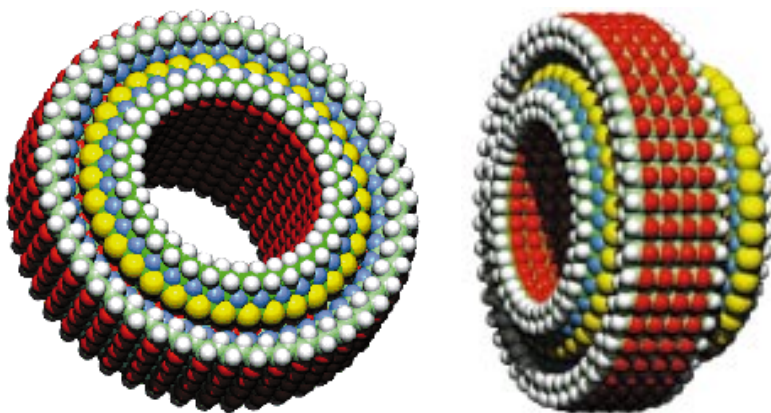
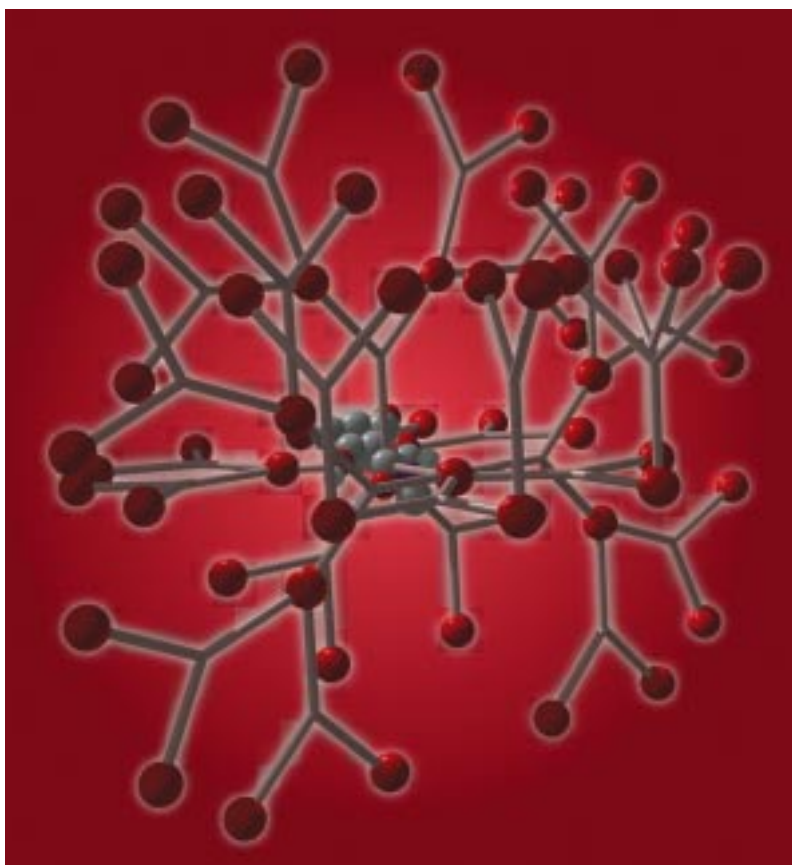


Figure 4.7.2

Artist's impression of a dendritic box carrying a drug molecule through the bloodstream.



The dendritic box [Jansen, 1995]

A poly(propyleneimine) dendrimer with amine end groups was modified with a rigid, closed aminoacid-derived shell in the presence of smaller guest molecules such as dyes or pharmacologically active agents. These guests were trapped inside the dendrimer and could only be liberated when the shell was partly or completely removed, depending on the size of the guest molecules. This principle can be used for controlled release applications. Figure 4.7.2 shows an artist's impression of a dendritic box.

pH-controlled release of acid dyes [Baars, 1997]

Fatty-acid-modified poly(propyleneimine) dendrimers were able to extract acid dyes from aqueous solution at low pH. When the pH was increased into the basic region, the dyes were released by the dendrimer into the water, again an example of controlled release.

Antenna function [Gilat, 1997]

By modifying the periphery of a dendrimer with light-absorbing groups, the dendrimer is able to absorb ('harvest') a broad range of (visible) photons. When an appropriate laser dye is put in the center of the modified dendrimer, the collected energy can be transferred to this dye, which in its turn can emit light at a single wavelength. This principle can form an efficient way to transfer light energy, analogous to light energy collection and transfer in biological systems.

Commercial aspects

From a commercial viewpoint, dendrimers are highly specialized products. Generally speaking, the cost of a dendrimer is related to its generation: for each additional generation of branches, the price will be approximately doubled. The mentioned high-tech applications of higher generations of dendrimers have a very high added value, so that a high price should form no objection. Production of this type of dendrimers will often take place on laboratory (maximum: kilogram) scale. Large-scale industrial applications are more often associated with lower generations. Conceivable applications of lower generations are, for example, crosslinkers in coatings, adhesives, surfactants and plastics additives. These types of applications are mainly based on the large number of reactive end groups. A number of these applications have been technically proven. At present, dendrimers are not yet available on a commercial scale. DSM is producing dendrimers on a multikilogram scale for testing purposes. It is expected that commercial applications will be realized before the year 2000.

Future developments

Over the last few years, attention has shifted from synthesis towards characterization. This has led to an increased understanding of the unique properties of dendritic macromolecules. Future research on applications will be based on this increased insight. The control of properties of dendrimers through appropriate chemical modifications is of increasing importance. This will ultimately lead to the possibility of fine-tuning of the dendrimers' chemical and/or physical properties for specific applications.

Partly depending on developments in supramolecular chemistry, the combination of dendrimers of one or more types into aggregated materials will be getting more attention. Dendrimers can also form a starting point for the development of synthetic systems mimicking the functionality of biological ones. The synthesis of nanoscopic inorganic particles in the interior of dendrimers has already been shown feasible and will probably be exploited within a few years. The development of larger-scale industrial applications will be generally realized within a few years. Next to dendrimers, hyperbranched macromolecules (if synthesized in a controlled way) will also be of importance for these applications because of their lower price.

Table 4.7.1

Molecular weight and size of three types of dendrimers. The molecule with one layer added to a central polyfunctional core is called generation 1. Molecular weight is expressed in atomic mass units (1.660×10^{-27} kg), i.e. 1/12 of the mass of the most abundant isotope of the carbon atom (^{12}C).

generation	poly(propyleneimine)		poly(amidoamine)		poly(benzyl-phenylether)	
	mol. weight	radius (nm)	mol. weight	radius (nm)	mol. weight	radius (nm)
1	317	0.4	359	0.5	576	0.7
2	773	0.7	1044	0.8	1212	1.0
3	1687	0.9	2414	1.1	2484	1.3
4	3514	1.2	5154	1.6	5034	1.7
5	7168	1.4	10632	2.0	10127	2.1
6			21586	2.7	20292	2.5
7			43451	3.4	40644	2.9
8			87227	3.8		
9			174779	4.5		

4.8 TRANSISTORS BASED ON ORGANIC MOLECULES

*T.M. Klapwijk*¹¹

In section 2.6, it was mentioned that in molecular-scale silicon-based electronics, semiconductivity can no longer be achieved by doping. In organic chemistry, a great many molecules contain alternating single and double bonds between carbon atoms. This alternation leads to semiconducting behavior. There is a valence band (HOMO-: highest occupied molecular orbital) and a conduction band (LUMO-: lowest unoccupied molecular orbital). These semiconducting molecules can serve as building blocks to manufacture an electrically active component, such as a thin-film transistor (TFT) [Garnier, 1994]. Examples of this kind of molecules are thiophenes, anthracene, pentacene, perylene. All these have been studied in the past by chemists and physicists because they form molecular crystals. This section explains how metal-insulator semiconductor field-effect transistors (MISFETs) can be built using organic semiconductors. Inorganic semiconductor electronics starts with a large monocrystalline wafer of silicon or gallium arsenide. Through a large number of modifying steps including oxidation, vapor deposition, doping and lithography, the wafer surface is transformed into a distribution of small interconnected transistors. All these steps can be controlled well and occur as part of a mass fabrication process, with the result that the integrated circuits have become very cheap. However, the demand for a monocrystalline, flat silicon wafer limits both the maximum surface and the macroscopic form. For some applications one would like to have active electronics in different shapes, for instance in a rounded form that can be glued on packing materials such as bottles. The well-known bar code that stores information passively could then be replaced by actively programmable electronics. This would find useful applications in theft protection, transport labels, etc. However, these electronic devices should be disposable, and hence cheap and easy to apply. Moreover, oxidation in air should not lead to loss of quality. The current interest in organic molecules has been sparked because they are in principle suited to make this sort of 'plastic' electronics. Dry-spinning the molecules from solution leads to a film of randomly placed organic semiconducting molecules. The molecules can be equipped with side groups to enhance their solubility or their mutual overlap in the dried form. When different layers are applied one after the other, another demand is that they do not mix. By placing this film above a polysilicon gate and connecting it to two gold electrodes functioning as source and drain, a well-functioning transistor can be fabricated that is fast enough for the applications mentioned [Brown, 1995 and 1997]. Variation in the semiconducting properties can be obtained by choosing the molecules and their ordering. At the same time it is obvious from a literature search that knowledge about the relation between the macroscopic current-voltage characteristics and the microscopic processes is still very much in its infancy.

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To bridge this knowledge barrier, a promising approach is currently under development in which the organic molecules are not thrown randomly on a stack, as is unavoidably the case when using dry-spinning from solution, but put neatly in a row on a substrate. For oligomers such as thiophene, this can be achieved by vapor deposition *in vacuo*. As mentioned, these substances tend to form molecular crystals. By a suitable choice of substrate, temperature and deposition rate, crystallites with dimensions of more than several micrometers can be obtained. This makes it possible to determine the electrical conductivity of a single crystallite of the semiconducting molecules.

Naturally, an important question for a scientist is if it is reasonable to expect the development of new knowledge along this path. For this reason it is good to discuss another aspect of the idea of molecular electronics. Traditional semiconductor physics uses electronic states that are referred to as extended states. This means that the probability to find an electron anywhere within the silicon crystal is equally large. (Localized states, for which the probability to find the electron has a maximum at a specific location, occur only under specific circumstances, for instance due to the presence of a defect). The reason behind the occurrence of extended states is that the conduction electrons are only loosely bound to the atoms forming the lattice, and can therefore be treated as moving freely throughout the crystal. However, this picture breaks down when the size of the crystal is diminished below a certain value. In a nanosized crystallite, the electron becomes confined within the geometric dimensions of the crystal, leading to localization. The resulting electronic states can be compared to those inside an atom, where the electron is confined by the attractive Coulomb potential. Hence these crystallites, which are studied by the new discipline of mesoscopic physics, are called artificial atoms. The picture of freely moving electrons breaks down even further for semiconducting molecules [Pope, 1982; Wright, 1995; Silinsh, 1994]. The charge carriers are not only connected to the molecules, but even strongly coupled to one or several atoms within each molecule. The molecule is in an excited, polarized state called a polaron. It is the polarons that move through the material, not the electrons. How the polarized excitation of the electron cloud is transferred from one molecule to the next is unclear, since it does also require a regrouping of the atoms involved. Moreover, the polarons' effective charge, effective mass (mobility) and magnetic moment (spin) are also unclear. Hence the mechanism of conduction in molecular electronic devices presents some interesting scientific questions, that are relevant for developing applications as well.

The method sketched above to obtain a well-constructed building out of molecular building blocks betrays the train of thought of a physicist used to working with sputtering and vapor deposition of thin layers in a vacuum system. However, as soon as one takes a somewhat broader view of the world of organic chemistry than merely as provider of building blocks for molecular electronics,

one quickly arrives at the technique of self-assembling monolayers. If one attaches ureum groups at the ends of thiophene molecules, a two-dimensional film consisting of adjoining chains of thiophene molecules forms spontaneously in solution. As a result, the thiophenes will be positioned neatly ordered flat on a substrate. Such a film is suited for integration with a substrate containing electrodes. This would be another step forward in the microscopic evaluation of the processes and the construction using molecular building blocks. Insight in the behavior of the molecular building blocks can only be obtained with this kind of well-characterized systems and hopefully that will also help provide a better understanding of how plastic electronics can be best developed. Which assortment of building blocks is needed remains to be seen. Creative nano-architects like a wide choice.

4.9 MOLECULAR SOLAR CELLS

*J.C. Hummelen*¹²

Introduction

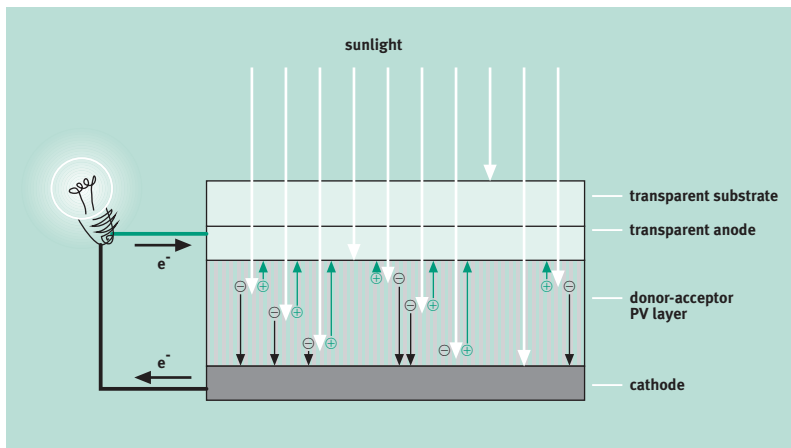
Sitting in a train and watching the world go by, you might occasionally see solar modules silently at work producing electricity. A steadily increasing number of buildings and boats are equipped with solar panels. You may find small photovoltaic (PV) arrays on emergency telephone boxes along interstate highways. These are only the very first messengers of what is planned to be a worldwide revolution in electric power production in the next 15 to 50 years.

At present, the active part of the typical commercial solar cells is made of silicon, either in the high-tech single-crystalline (sc-Si) form used in the chip industry, or in the cheaper and somewhat less-efficient multi-crystalline (mc-Si) form. The thickness of the silicon layer in these devices is on the order of 0.2 mm, making the material costs per square meter a real bottleneck in the competition with conventional (gas- and coal-based) electricity production. Nowadays, most research in photovoltaics is directed to thin-film devices (figure 4.9.1) [van Roosmalen, 1995]. In such solar cells, the thin photovoltaic active layer is supported by some low-cost supporting material, which can even be mechanically flexible. Micrometer-thin layers of amorphous silicon (a-Si), copper indium diselenide (CuInSe₂), or cadmium telluride (CdTe) as light absorbing materials are thick enough to absorb the bulk of the incoming light. Even thinner layers are sufficient when strongly absorbing organic dyes are used such as conjugated (containing alternating double and single bonds in the main chain) organic polymers and some low-molecular-weight organic dyes. They allow for a light-absorbing film thickness of only 100 to 300 nm, i.e. the molecular scale for polymers! A single monomolecular layer of a dye with 2-nm-thick molecules is not thick enough. However, nanocrystalline particles of semiconducting titanium

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Figure 4.9.1

Basic working principle of the thin-film plastic photovoltaic (PV) cell. Absorption of a photon in the donor-acceptor photovoltaic layer results in a positive charge (\oplus) on a polymer chain and a negative charge (\ominus) on a fullerene molecule: charge separation. These charges move in opposite directions through the polymer and the fullerene material to the anode and cathode, respectively, because of the electric field between the two electrodes (made of different materials). When the circuit is closed, an electrical current can circulate with the photovoltaic device acting as the 'pump', making, for instance, a light bulb glow.



dioxide (nc-TiO_2) can be sintered to obtain electrical (ohmic) contact between the particles. The resulting porous network of particles can subsequently be coated with a single layer of organic dye molecules. In that case, most of the incoming light is absorbed by the structure because the photons encounter many monomolecular layers. The latter is the principle of the solar cell developed by M. Grätzel, which is a product of nanostructured materials technology *avant la lettre!* [O'Regan, 1991] (section 1.2). In 1997, the best small-scale nanocrystalline TiO_2 dye cells turned the earthly solar spectrum of light into electric power with a conversion efficiency of $\sim 10\%$, which is only a few percent less than the typical efficiency of commercial multicrystalline-Si-based photovoltaic modules. Other molecular photovoltaic devices based on organic molecules ('organic' or 'molecular' solar cells) show efficiencies below 2%, but new concepts are being developed that are expected to raise the efficiency significantly. Below, we will focus on these new concepts, especially on those involving nanostructured mixtures of (macro)molecular donor-acceptor pairs to yield 'plastic' solar cells.

Fundamental differences between inorganic and organic solar cells

In classic *inorganic* solar cells, a junction between two semiconducting materials (e.g. n-type Si and p-type Si) provides an internal electric field. Hence, when charges (electrons and holes; e^- and h^+) are generated upon absorption of light, they move away from the junction in opposite directions. The charges can be collected at the bottom and the top of the device. The charge-carrier mobility in inorganic semiconductors is relatively high, hence, the charges can travel 'far' (hundreds of microns) without getting trapped.

In *organic* semiconductor materials, the charge-carrier mobility is invariably low. Inside the molecules the mobility can be very high. The fundamental problem is that the charges have to hop from one molecule to another many times in order to travel. Two molecules have to be really close and well-oriented in order

to allow for efficient charge hopping. Hence, crystalline organic materials (close and well-oriented molecules) and conjugated polymers (long molecules: less hopping if they are aligned in the right direction!) show the highest but still modest charge-carrier mobility. Liquid crystalline order can also help the hopping process.

Another fundamental difference between inorganic and organic semiconductor materials is present in the way the charges are generated: In organic materials, the initial step upon absorption of a photon is the formation of an electronically excited molecule in which the e^- and h^+ are only slightly separated and still tightly bound; i.e. an exciton. Depending on the type of material, this exciton can migrate somewhat like individual charges can, but one of the charges of the exciton has to be transferred to another molecule in order to form a truly separated pair of charges that can travel independently. The acceptor molecule has to be close to the donor molecule; otherwise the exciton doesn't survive the trip. Because of both mobility problems, organic solar cells, built with micron-scale-thick layered structures of donor and acceptor molecules like n-type and p-type layers in inorganic solar cells, don't function well. The scale of architecture in organic photovoltaic devices has to be brought down to the scale of the mobilities of the excitons and the separated charge carriers in these materials: the nanoscale.

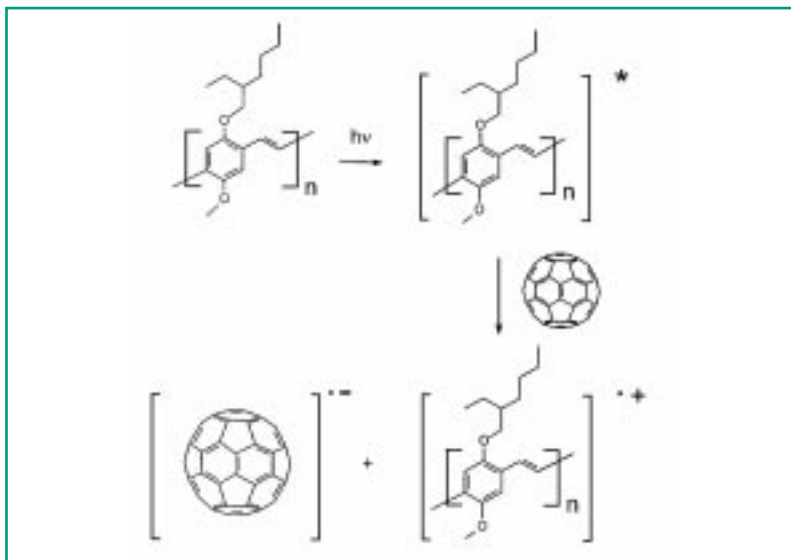
Spontaneously nanostructured 'plastic' solar cells

A very elegant example of nanoscale architectural design for a molecular solar cell is known under the somewhat misleading term 'bulk-heterojunction' [Yu, 1995a; Halls, 1995]. In the ideal case, two regular, continuous, and interpenetrating networks of donor-molecules and acceptor-molecules make the photovoltaic active layer, sandwiched between two different electrodes. The donor and acceptor networks have two functions: first, upon irradiation, opposite charges are generated in each network; second, each network transports only one type of charges to the corresponding electrode. Because the bulk-heterojunction is not a junction in the semiconductor sense, i.e. it does *not* give rise to an internal electric field in the right direction for the charges to move to the electrodes, the electric field has to be provided by two electrodes with different work functions. This is no problem when a thin donor-acceptor film is used. The great nanotechnological challenge is how to obtain the ordered interpenetrating donor-acceptor networks structure in the film.

Although, until now, the principle of the bulk-heterojunction has been realized only in crude form, the photovoltaic efficiency results are very encouraging. Two kinds of bulk-heterojunctions are of special interest: one consisting of two types of conducting polymers (2CP cell) [Yu, 1995a; Halls, 1995] and the other consisting of a mixture of a conducting polymer and bucky balls (C_{60}) or, better, a fullerene derivative (CPC cell) [Yu, 1995b]. The 'two conducting polymers cell'

Figure 4.9.2

Photo-induced electron transfer from a conjugated polymer (MEH-PPV) to a bucky ball (C_{60}) takes place in two main steps. First, the conjugated polymer absorbs a photon of light and becomes electronically excited; second, this excited molecule transfers an electron to a nearby bucky ball within 3×10^{-13} seconds. The result is a radical pair of ions with opposite charge.



is made by simple spin-coating of a mixture of two conjugated polymers, one serving as the electron donor and transport medium for holes and the other as the acceptor and transport medium for electrons. Interpenetrating networks are formed spontaneously in the plane of the film. A nanostructured blend is formed because polymers do not mix well on the molecular level; they phase-separate when the solvent evaporates. The scale of the resulting morphology is in the nanorange quite often. Nanoscale morphology is also observed in a spin-cast film consisting of a mixture of a conjugated polymer and the molecularly perfectly spherical bucky ball [Yang, 1997]. Although such a phase segregation in blends of a conjugated polymer and other fullerenes has not been proven to exist, it is very likely that the functioning of solar cells made from this material is also based on the principle of a bulk-heterojunction.

Bucky balls serve as an electron acceptor in the combination with a number of conjugated polymers [Sariciftci, 1992]. The photo-induced electron transfer from the light-absorbing polymer to the fullerene occurs within an astonishingly short period of time: 0.3 picoseconds (3×10^{-13} s). This is so fast that no other disturbing process can compete. Hence, the efficiency of photo-induced electron transfer is 100% in this case. Moreover, since the electron transferred state can exist for as long as 1 ms, this allows for quite some time for the charges to be transported to the corresponding electrodes. That is a *very* good starting point for constructing a photovoltaic device! The basic events in this photo-induced electron transfer are depicted in figure 4.9.2.

Since a bucky ball is a low-molecular-weight spherical molecule, the percentage needed in the mixture with a conjugated polymer to obtain a continuous fullerene network is estimated to be $\sim 15\%$. The limited solubility of bucky balls excludes the possibility to make such mixtures. This problem has been over-

come by replacing bucky balls by soluble fullerene derivatives, resulting in the most efficient plastic solar cells known to date [Yu, 1995b].

Future directions for plastic solar cell research

The spontaneous nanostructure obtained in blends of conducting polymers (zCP) or of conjugated polymers and bucky balls (CPC) is still a very disordered one. Although the constituents most likely form continuous networks, they may be so irregular that the charge carriers have to travel small distances *against* the electric field supplied by the two electrodes. There is little doubt that this seriously hampers the efficiency of present plastic photovoltaic devices.

By designing building blocks that self-assemble and assemble with other molecules to make supramolecular architectural structures of high order, it should be possible to obtain more regular interpenetrating networks, preferably directed towards the electrodes. Making such nanostructures is a huge synthetic challenge! In figure 4.9.3, the present random interpenetrating network and a possible future form of a well-organized network are shown schematically.

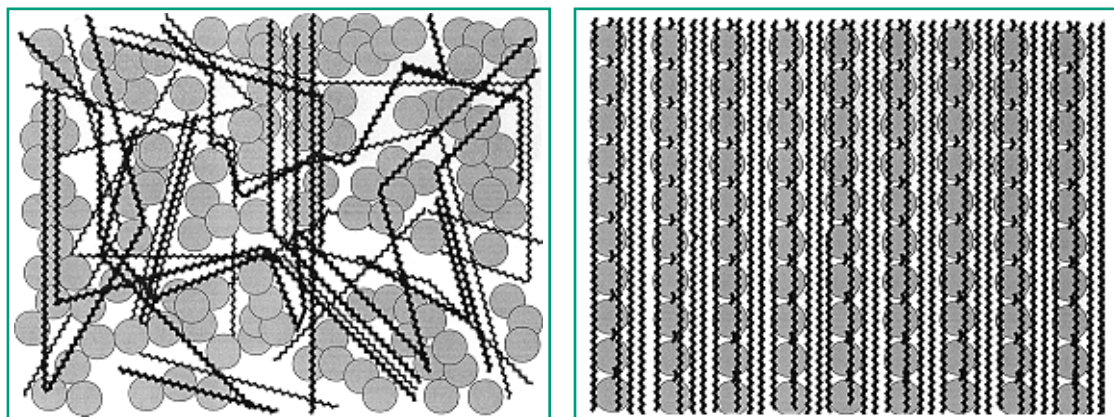
The fullerene component does not contribute significantly to the absorption of light by the photovoltaic device. Hence, the concentration of this component should be as low as possible in order to allow a thin film to absorb most of the incoming light. However, if the fullerene component has to serve as the electron transport network, it has to be present in an amount above the threshold for forming a continuous network (the percolation limit). This threshold would be lowered drastically if well-defined, soluble, and processable polymer forms of fullerenes would be applied.

At present, the conjugated polymers used in photovoltaic device research, have not been optimized for absorbing the solar spectrum of light. Important parameters for conjugated polymers to be useful are: chemical purity, regularity, processability, band gap, ionization potential, stability, charge-carrier mobility, assembling sites, availability, and, eventually, cost of production. Optimizing the (nano)morphology of blends of conjugated polymers, a conjugated polymer

Figure 4.9.3

Left: a schematic view of the present random mixture of conjugated polymer and bucky balls (or fullerene derivatives).

Right: A possible form of a well-organized (supramolecular) mixture of a conjugated polymer and a fullerene derivative.



with a fullerene derivative, or mixtures of three components, is a new field with enormous potential for plastic photovoltaic devices.

Device stability, although expected to improve with increasing efficiency, is a major concern for molecular optoelectronic devices in general. Much can be learned from closely related areas of research such as photodiodes, molecular integrated circuits, nonlinear optical devices and light-emitting diodes. Light-emitting diodes based on self-assembling polymers have recently been realized on a lab-scale [Service, 1998].

Plastic solar cells can be envisioned to come in new formats, like in transparent (using infrared light only) or colored semi-transparent windows. Flexible and lightweight photovoltaic foil, that can be cut to the desired format, and that can be produced using relatively cheap methods like spaying or printing techniques, could find widespread application if it is stable for at least several years.

4.10 COMPUTATIONAL NANOTECHNOLOGY

R.M.A. Knegt, P.D.J. Grootenhuys¹³

Although the application of computational techniques, especially molecular dynamics, to biomolecular systems has become routine, the treatment of biochemical phenomena involving the mechanics and dynamics of large protein assemblies on a nanometer scale has been limited. A molecular dynamics simulation is a computer calculation of the time evolution of the atomic and molecular positions and velocities of the system using the laws of classical mechanics [Karplus, 1990; van Gunsteren, 1990]. The calculated positions and velocities are converted into experimentally accessible quantities such as temperature. Factors limiting the simulation of such systems are their inherent heterogeneity and flexibility and the computationally intensive modeling of solvent. Contemporary computer power is insufficient to simulate molecular dynamics beyond the nanosecond timescale.

A complete overview of all protein structure prediction and design approaches falls outside the scope of this paper, but the potential impact on the design of biomolecular systems with nanoscale dimensions is enormous. To illustrate the current state-of-the-art in de novo protein design, we refer to the recent work of Mayo and co-workers, who successfully designed, produced and validated the structure of a novel protein that folds in a way similar to a target zinc finger protein [Dahiyat, 1997].

Nanoscale devices

Given the complexity of biomolecular systems, simpler synthetic molecules may form a more fruitful area for exploratory theoretical research. Although true molecular machines have yet to be invented, recent advances in supramolecular

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chemistry and physical techniques for the manipulation and study of individual atoms have laid the foundations for such devices. Current research focuses on the feasibility and properties of separate components of molecular machines, such as molecular switches, motors, bearings, etc. Techniques from computational chemistry have therefore mostly been applied to predict the stability and behavior of such components. Since such components consist mainly of hundreds of mostly carbon atoms, traditional molecular mechanics and dynamics approaches are quite suitable.

In particular, molecular bearings (figure 4.10.1 on page 242) have received much attention in simulations. An important initial result was the discovery that molecular bearings can be made to operate with minimal friction without the use of lubricants as was suggested first by Drexler [Drexler, 1986] and rationalized by Merkle [Merkle, 1993]. This result was obtained without explicit simulation of the molecular bearing but derived from a mathematical analysis of the symmetry and intermolecular interactions between two nanotubes. More detailed picosecond molecular dynamics simulations were reported later for bearings made of graphite tubes up to 12 nm long [Tuzun, 1995]. In this work, momentum was added in opposite directions for the shaft and sleeve. The dynamic behavior was studied by monitoring physical quantities such as the angular momentum and the interaction energies during the simulation. The bearings in the simulation showed typical mechanical effects such as beats during rotation when more than one type of vibrational motion is possible and temperature and velocity dependence of friction. The same authors also reported a molecular dynamics simulation of laser-driven bearings that were made to rotate by exposing charged groups at the shafts ends to an oscillating electric field. The dependence of the motor's on and off times on size, charge position, frequency and field strength were modeled using a neural network programmed to facilitate the design of such systems. Although the network was able to model the simulated on/off times of the motor within 2% error for the training set and 10% error for a test set of the above mentioned parameters, no parameters could be found that would allow the motor to perform continuously [Tuzun, 1995]. A movie¹⁴ of a computer simulation of a rotating molecular bearing can be found at the World Wide Web. Although rigid structures such as diamond- or graphite-based bearings simplify many of the calculations needed to simulate their behavior, the size of systems to be simulated in the future (i.e. complete molecular machines consisting of thousands of atoms) still surpasses the capabilities of currently available simulation hardware and software [Saini, 1996]. Interestingly, the development of more powerful computer hardware, needed to deal efficiently with large aggregates in atomic detail, appears to depend on the advancement of nanoelectronics (chapter 2). Although specialized program packages designed to simulate the dynamics of rigid molecules using techniques from finite element analysis and parallel computing have been reported

¹⁴ <http://science.nasa.gov/Groups/Nanotechnology/gallery/>

[Hanyzewski, 1996], simulation tools that do not use atomic detail may be more promising.

An example of reasonable agreement between experimental results and computational predictions is the conductivity of nanotubes. A single carbon nanotube (figure 4.10.2) can function as a nanodevice [Collins, 1997]. Depending on the helicity of the tube, carbon nanotubes can transport currents either as metals or semiconductors. Introducing lattice defects at the boundary of two nanotubes alters their relative helical twist. This has important consequences for conductivity in accordance with theoretical investigations into the effects of various lattice defects [Chico, 1996a]. In the experiment, the conductance of individual carbon nanotubes was measured using a scanning tunneling microscope (section 5.2) and abrupt changes in conductivity at distinct positions on the tube were observed. These observations correlated well with calculations.

Figure 4.10.2

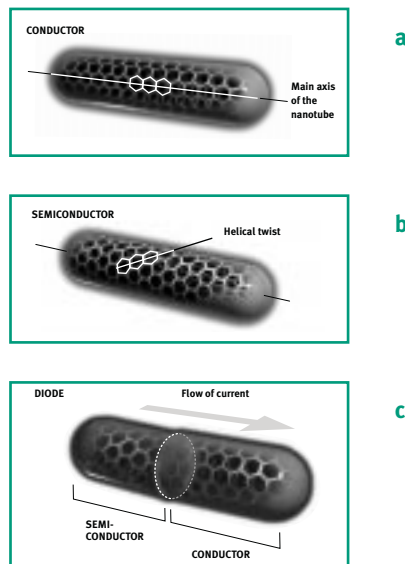
The conducting properties of nanotubes:

a *When the carbon rings line up with the main axis of a nanotube, the molecule conducts electricity like a metal.*

b *A twisted pattern of hexagonal rings leads to semiconducting behavior.*

c *Two single carbon nanotubes joined together act as a diode.*

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In particular, the occurrence of so-called pentagon-heptagon pairs in the normally hexagonal lattice of the carbon nanotubes was found to induce a bent local structure and reduced conductivity, causing the experimentally observed localized conductance gaps. Such conductivity gaps, which can be altered by electromagnetic radiation or mechanical manipulation, could make carbon nanotubes suitable for the construction of nanoscale switches [Chico, 1996b].

Simulating nanofabrication

An even more complex problem than the behavior of rigid components of molecular devices is the simulation of their fabrication. Essentially two different methods exist for building nanostructures bottom-up, mechanosynthesis and self-assembly [Drexler, 1994].

Mechanosynthesis

Mechanosynthesis involves the placement and connection of individual atoms either by using tools from atomic force microscopy or the possible use of molecular machines or templates for controlled synthesis [Drexler, 1992]. These techniques can effectively increase the local concentration of reactants and catalysts and greatly improve the accuracy and speed of synthesis, just like enzymes. In addition to the difficulty of simulating the molecular dynamics of the rupture of a protein-ligand complex by atomic force microscopy techniques, the simulation of the effects of macroscopic manipulation of microscopic systems remains difficult. This is due to the differences in resolution and time-scales, especially since the placement of individual atoms requires the use of *ab initio* quantum chemical calculations. Such methods have been used to model the abstraction of a single hydrogen atom from various model compounds [Mussgrave, 1992], but are still cumbersome for large numbers of atoms [Merkle, 1991].

Self-assembling systems

More applications of computational chemistry tools are found in the area of self-assembling molecules forming supramolecular structures of nanoscale dimensions. Although problems in this field are similar to those encountered in the simulation of mixtures of organic molecules or biomolecular systems, the simulation techniques are well established. The job is made easier because these simulations do not need to deal with differences in scale between molecular aggregates and the macroscopic devices used to construct them (as in mechanosynthesis). Even relatively simple approaches can be successfully applied to model macroscopic behavior. An example is the description of diffusion-determined growth of porous silicon aggregates that are of interest because of their photoluminescence. In this case, the growth of fractal silicon structures was modeled by making random walks on a grid under the influence of a force field [Smith, 1988].

The simulation of self-assembly by organic molecules in solution requires more detailed techniques, from energy minimization and visualization of possible complexes to extended molecular dynamics simulations of such complexes in solution. The main focus here is to understand and predict the stability of different complexes, rather than the actual process of aggregation. The results of molecular dynamics simulations are often used in a qualitative sense because the aggregates are too large for quantitative results, the inclusion of solvent in the simulation is computationally demanding and because thermodynamic free energies are difficult to extract. An example is the supramolecular hydrogen-bonded aggregate of cyanuric acid and melamine [Whitesides, 1995]. Molecular dynamics simulations of this system were carried out with an explicit solvent (chloroform) or without (either *in vacuo* or using Langevin dynamics, representing a coupling to a heat bath and thus providing a means to control

and maintain temperatures). The results showed that some representation of the solvent is essential. In particular, structures simulated *in vacuo* were unstable and, in fact, a chloroform molecule was observed to enter a cavity at the center of the aggregate [Chin, 1994]. Since the calculation of equilibrium constants or thermodynamic free energies would have taken too much computer time, other means of predicting the stability of such non-covalent complexes were sought. During the simulation, the vibration of the atoms within the hydrogen-bonded rings induced temporary shape deformations. It was found that the time-averaged deviation of planarity of the rings provided a useful parameter for predicting their stability.

Another interesting example is the computational analysis of triblock copolymers. Analogous to diblock molecules, these are polymer chains consisting of three parts that are chemically different. The different parts within the chain may attract or repel each other. The balance between repulsive and attractive interactions was calculated for a model triblock copolymer containing molecularly rigid and flexible chemical sequences [Stupp, 1997]. The calculations indicated that the forces among densely packed molecular segments are attractive for rigid blocks and repulsive for flexible blocks of styrene-isoprene. The balance between these interactions can mediate the formation of supramolecular units such as spheres or cylinders.

Dendrimers

In the field of dendrimers, computational tools are used mainly for illustration and visual analyses purposes. The choice and design of the chemical building blocks was mostly inspired by 'general organic chemistry considerations' rather than by computational analyses [Moore, 1997].

Conclusions and perspective

The ability to effectively design and model molecular machines and devices is one of the key research objectives in molecular nanotechnology. In principle, computational techniques may be of great help for this. Conventional molecular mechanics and dynamics methods provide ample tools for modeling small nanodevices and aggregates. However, so far only few examples have been published describing computational design of nanostructures. Limiting factors are the size and complexity of the structures involved, the absence of special design tools, and a proper description of solvents. New methodology and possibly new computing hardware are required for the study of larger structures and aggregates in which large numbers of atoms and the effects of solvation demand extremely long calculation times. For rigid components of nanodevices, a simplified representation may prove useful. On the other hand, the effects of solvent on nanomachine functioning may require more detailed analysis, as does the mechanical manipulation of individual atoms. Simulation of non-

covalent aggregates in solution would benefit from more general approaches to estimate the stability of such complexes. The assessment of complex stability is similar to the problem of estimating protein-ligand binding free energies and an exchange of ideas between these fields is expected to be fruitful.

Once the problems mentioned above have been solved, tools can be developed for the actual design of nanostructures. The lack of these tools still forms a major bottleneck for the practical application of molecular nanotechnology. Still, computational nanotechnology is a rapidly developing field and methodological advancements can be expected that might also prove useful in other areas of computational chemistry.

4.11 PROTEINS: A SOURCE OF INSPIRATION

*J.M. van der Laan*¹⁵

Introduction

This section explains the relevance of protein chemistry for molecular nanotechnology. As indicated in section 4.1, biotechnological methods are relevant for molecular nanotechnology insofar as they can be used for applications with properties that depend on those of the individual molecules, such as nanosized drug-loaded vesicles, molecular electronic devices or molecular machines. Protein folding is discussed because it is essential for the rational design of proteins.

Natural proteins consist of combinations of 20 different aminoacids linked by so-called peptide bonds to form a polypeptide chain. Inside living organisms, proteins have various functions such as catalysis, transport and storage of energy, coordinated motion, immune protection, mechanical support, control, signal and energy transduction. Proteins that catalyze chemical reactions are called enzymes. Their ability to recognize and transform molecules makes them candidates for integration in future molecular machines. Nobel-prize-winner Richard Smalley considers them essential as the 'fingers' located at the extremities of future powerful molecular assemblers [Smalley, 1997]. The ability of proteins to specifically recognize other molecules is common to all functions. They may recognize each other and form large assemblies, but they may also recognize small molecules, ions, or macromolecules such as DNA and RNA, lipids (one of the main components of the cell membrane), and carbohydrates. A well-known example of the vital importance of highly specific recognition by proteins is the immune system. It identifies and selectively destroys, removes or encapsulates any body-foreign material.

Natural proteins are produced inside living cells by the ribosome (figure 4.11.1), a 30-nm large functional assembly of proteins and RNA. The ribosome manufactures proteins (typical size 1 to 10 nm), including copies of its own proteins,

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Figure 4.11.2

Schematic picture of a flagellar motor. Its stationary element (stator) consists of about twelve motility (Mot) complexes embedded in the cell membrane. Its rotor element (rotor), the C ring, is mounted onto the flagellar body and projects into the cytoplasm. It consists of about 30 copies of three different proteins and is about 50 nm in diameter. Protons (H^+) are at a higher electrical potential and/or concentration outside the cell than inside. When they pass through a trans-membrane channel, they expend their energy to generate a torque between the two structures. Reprinted with permission from [Macnab, 1998]. Copyright 1998 Gordon and Breach Publishers.

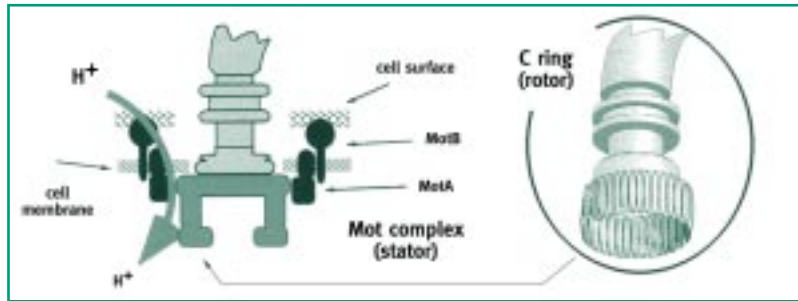
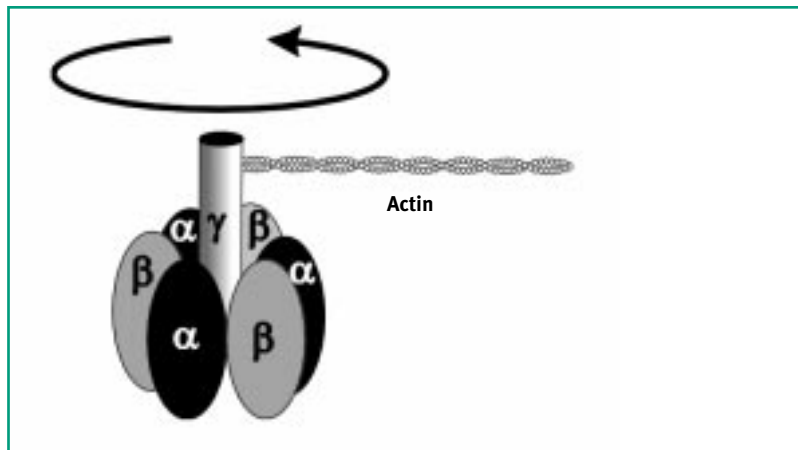


Figure 4.11.3

Schematic drawing of the smallest known rotary motor, which consists of a single molecule (F_1 -ATP synthetase). A central rotor about 2-nm in diameter, formed by its γ -subunit, turns in a stator barrel about 10-nm in diameter formed by three α - and three β -subunits. The rotor is powered by a membrane-embedded proton-conducting unit (F_0) and the actin filament is attached as a marker for the experimental observation of rotation. Reprinted with permission from Nature [Noji, 1997]. Copyright 1997 Macmillan Magazines Limited.



according to the instructions derived from the genes, and is often referred to as an example of a molecular machine. Theories on molecular information theory¹⁶ and the practical limits of such molecular machines are being developed by theoretical biologists [Schneider, 1997]. In chromosomes, proteins wrap the DNA string, which in itself can be up to centimeters long, into a compact protein-DNA package. In viruses the so-called coat proteins assemble spontaneously into large nanobodies that pack and transport the viral RNA or DNA to new hosts. In transport across membranes, signaling phenomena and energy transduction,

the embedding of proteins in membranes is often essential. Some protein complexes, such as ATP synthetase (the enzyme complex synthesizing ATP), the bacterial flagellum motor and the kinesin motor, act as small rotary motors, converting chemical, electrical and pH gradients into motion (figure 4.11.2). The efficiency of the kinesin motor has been determined at about 40% [Gittes, 1996]. The ultimate biomolecular assembly is the cell. Proteins as well nucleic acids provide an excellent proof of concept for the storage of information, precise chemical catalysis and signal transduction at the molecular level. Besides tasks that focus on the binding, transformation and transport of chemicals, proteins also perform activities reminiscent of mechanical devices. The ATP synthetase complex uses proton- or sodium-motive force

¹⁶ <http://www-lmmb.ncifcrf.gov/~toms/>

Figure 4.11.1

3D reconstruction¹⁷ of a yeast ribosome (blue) bound with the protein-conducting channel (red), viewed from below (left figure) and in cross-section from the side (right figure). The bar indicates 10 nm.

Proteins are formed in the ribosome according to the instructions from the genes via the messenger RNA. The passageway of newly formed proteins is indicated by the dashed line in the right figure. They are exported through a tunnel between the two ribosome subunits (40S & 60S), and exit through the donut-shaped (see right figure) protein-conducting channel. The arrow indicates that the stem of the ribosome connects it to the protein-conducting channel. The precise working of the ribosome is an ongoing field of study. Reprinted with permission from [Beckmann, 1997]. Copyright 1997 by The American Association for the Advancement of Science.

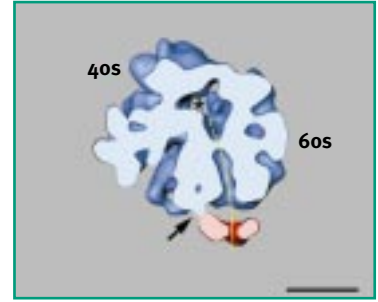
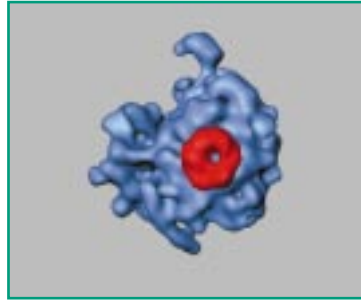


Figure 4.11.4

The structure¹⁸ of tubulin at 0.37-nm resolution obtained using electron crystallography. It shows the protein to be a dimer consisting of two monomers that are almost identical in structure. Each monomer is formed by a core of two beta sheets (green) surrounded by helices (blue), and each binds to a guanine nucleotide (pink). In addition to a nucleotide binding site, each monomer also has two other binding sites, one for proteins, and one for the promising anti-cancer drug Taxol[®]. Tubulin polymerizes into long chains or filaments that form microtubules, hollow fibers that serve as a skeletal system for living cells. Courtesy of E. Nogales.



17 <http://www.sciencemag.org/cgi/content/full/278/5346/2123>

18 <http://www.lbl.gov/images/PID/dimer.jpg>

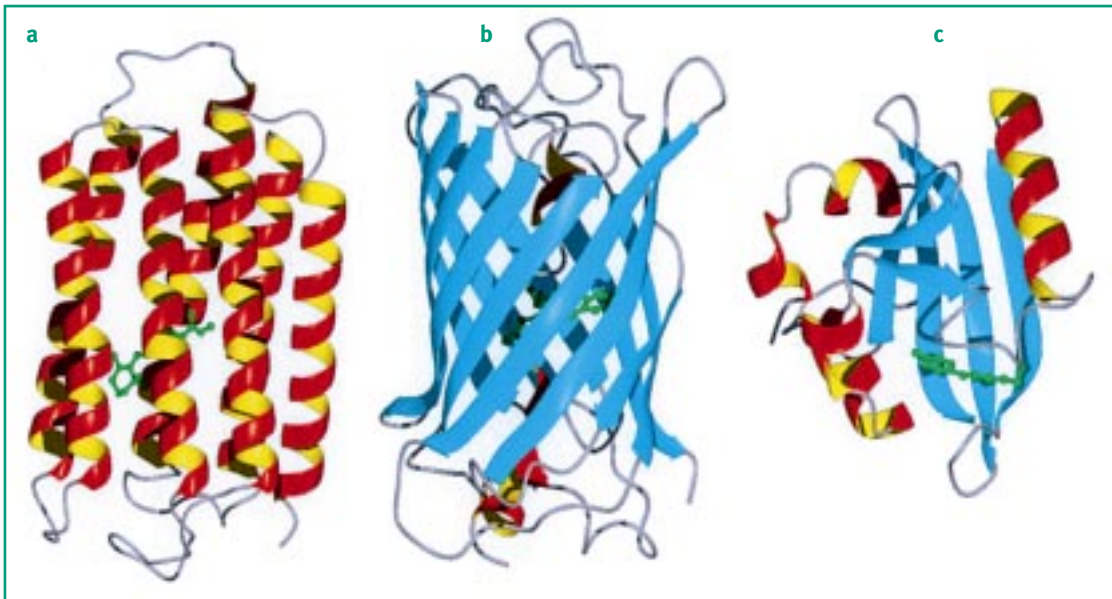
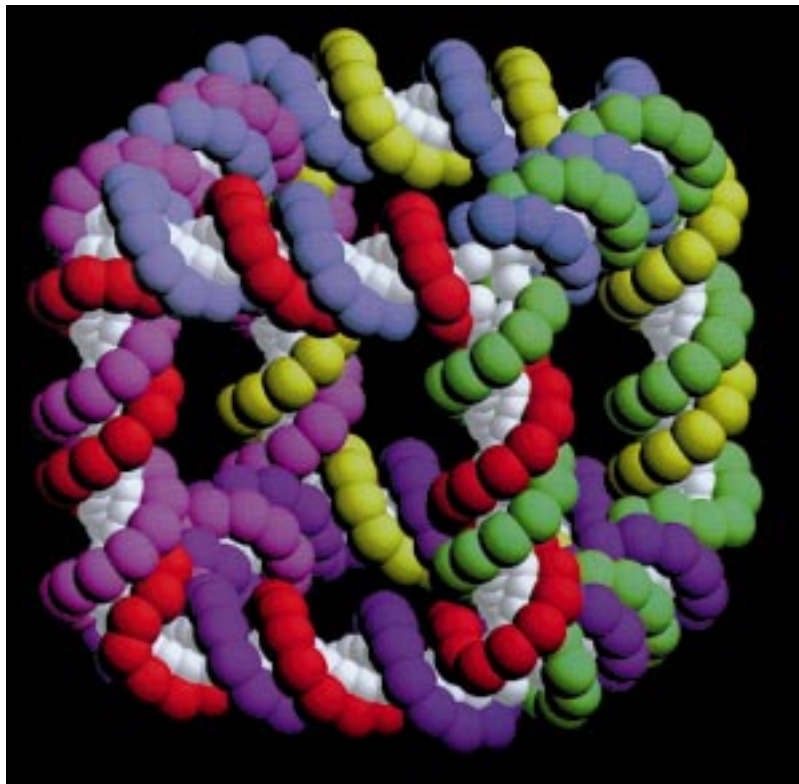


Figure 4.12.2

Protein structure of: (a) bacteriorhodopsin (BRh), (b) green fluorescent protein (GFP) and (c) photoactive yellow protein (PYP). GFP and PYP are water-soluble up to high concentrations. Bacteriorhodopsin is shown with the intracellular side upwards. The pitch of the α -helical elements (red/yellow) equals 0.54 nm in each panel. Thus the length of the α -helical elements in BRh is approximately 0.4 nm, while GFP and PYP are depicted 1.4-fold enlarged compared to BRh. Source: the Protein Data Bank [Abola, 1987; Bernstein, 1977]. See text on page 265 and further.

Figure 4.14.1

DNA cube²³: structural model of the first synthetic DNA molecule in the form of a closed polyhedral object. It contains six different cyclic strands. Each nucleotide is represented by a single colored dot for the backbone and a single white dot representing the base. Note that the strands are linked to each other twice on every edge. To get a feeling for the molecule, follow the red strand around its cycle around the front square: It is linked twice to each of the four strands that flank it, and only indirectly to the strand at the rear. Note that each edge of the cube is a piece of double helical DNA, containing two turns of the double helix [Seeman, 1997]. See page 278.



²³ <http://www.foresight.org/Conferences/MNT05/Papers/Seeman/index.html>.

This web-article contains several other graphic examples.

to produce ATP from ADP. The enzyme contains three active sites, which cycle through stages of being empty and having ADP or ATP bound, respectively. During catalysis, the γ -subunit is rotated similar to a crankshaft, coupled to the release of ATP [Junge, 1997]. This motion was experimentally detected (figure 4.11.3 on page 258). Similar mechanical actions are known, for instance, for the bacterial flagellar motor [Schuster, 1994]. Indeed, proteins as well as DNA have been suggested as basic materials for artificial molecular machines [Drexler, 1994].

Protein folding

On the face of it, a protein is just a chain of aminoacids linked together by peptide bonds in an arbitrary sequence. The immense diversity of protein structure and protein function can be obtained with only twenty building blocks, because in a protein of n aminoacids, the aminoacids can be lined up in 20^{n-1} ways.

In order to extend their functionality even further, many proteins use inorganic ions or complex organic molecules for their activity. These so-called cofactors are, in turn, synthesized in specific enzymatic pathways.

Once in existence, an aminoacid chain in solution starts to fold in three dimensions under the influence of the weak interactions between the different building blocks along the chain. The folding is a relaxation process that reduces the thermodynamic free energy of the system until it reaches a minimum [Makhatadze, 1995]. The resulting conformation determines the properties and function.

For a natural protein under the appropriate conditions, all chains fold into the same, unique three-dimensional structure. This makes proteins suitable building blocks for molecular nanotechnology. In contrast, most artificial aminoacid chains just behave as a floppy or random coils, and applications of these proteins depend on their average properties only. Hence in order to be relevant for molecular nanotechnology, artificial proteins must fold into a unique structure as well.

This provides a major challenge for protein chemistry. Theoretical methods for the calculation of the precise thermodynamic free energy would allow ultimately for the rational design of proteins. Such calculations require highly accurate input parameters that cannot be theoretically determined. High accuracy is needed because the net energy balance stabilizing the protein structure is a sum of large positive and negative interaction energies. The explicit inclusion of the solvent in the calculations further increases the complexity. As a result, the final conformation cannot yet be predicted in general from the known sequence. The thermodynamic phenomena that underlie the organization or folding of the peptide chain also hold when considering the formation of complexes between individual proteins or complexes between proteins and substrates.

Understanding the mechanisms underlying such self-organization form a major challenge and a source of inspiration for protein science as well as molecular nanotechnology.

Analysis of protein structure

To understand how molecular components organize into complex assemblages of nanoscale dimensions, one must elucidate the three-dimensional structure. Currently most macromolecular assemblages larger than 10 nm are approached by a combination of techniques [Johnson, 1996; Wright, 1996; DeRosier, 1997]. NMR (nuclear magnetic resonance) spectroscopy can resolve the atomic structure of protein molecules in solution and, thus, provide insight into the natural flexibility of a molecule. It is, however, limited to structures smaller than about 3 nm. Electron microscopy, on the other hand, can handle larger objects, but achieves atomic resolution only for crystalline specimens. A recent example of a protein structure obtained at high resolution by electron crystallography is shown in figure 4.11.4 on page 259. Atomic force microscopy (section 5.3) is able to study surface topographies of biological specimens in solution, enabling the detection of conformational changes at subnanometer resolution.

The present knowledge of protein structure and related issues such as catalytic activity, folding, ligand binding and molecular recognition is mainly founded on a large number of three-dimensional structures that have been determined to atomic resolution by single crystal x-ray diffraction (also called x-ray crystallography). Although x-ray crystallography can access much larger structures than nuclear magnetic resonance, data interpretation becomes difficult for very large objects. The major obstacle, however, is the difficulty of obtaining large enough crystals of the proteins. This obstacle also makes it very hard to use x-ray crystallography to resolve the structure of one-dimensional assemblies such as nanotubes or of two-dimensional assemblies such as molecular films and membrane-like structures. The crystal environment also restricts the structural flexibility. As a consequence the insight in the dynamics of the molecular structure is limited to only those conformations that can be trapped in a crystal form.

Examples of structural assemblies of nanoscale dimension that were solved at atomic resolution are a chaperonin molecule, which assists in the folding of proteins (a barrel of 14×15 nm); the proteasome, which chops up unwanted proteins for disposal or display to the immune system (a barrel that is strikingly similar to the chaperonin); a heavy riboflavin synthetase, which turned out to be a bifunctional catalytic assembly with striking resemblance to the structural organization of viruses (an icosahedral capsid (proteinaceous covering) with 7-nm diameter); and last but not least the least the three-dimensional structure of complete viruses, such as the common cold virus with dimensions up to 50 nm. Because these large complex assemblages are difficult to assess by x-ray crystallography, the assemblages are reduced to their smaller components, which are studied to atomic resolution by x-ray crystallography or nuclear magnetic resonance. The assemblage is subsequently generated by docking the atomic models in lower-resolution maps of the whole structure that are obtained by small-angle neutron and x-ray scattering, electron- and atomic force

microscopes. Examples of such studies involve the complexes of viruses with receptors, of complexed proteins interacting with each other and with elastic elements such as in vertebrate muscles, or with membranes in the case of the photosynthetic reaction center and the molecular pores, with RNA in the ribosomes. The determination of the structure of protein complexes in combination with protein engineering, molecular genetics and many other physical methods is essential in understanding how a given structure relates to its function [Block, 1997].

Protein engineering

Protein engineering is a technology that encompasses the design, the construction and the production of modified proteins by genetic engineering. The genetic material of a particular fungi, yeast or a bacterium producing the protein is altered in such a way that it produces a modified version. Together with cloning technology, this allows for easy and unlimited reproduction of the modified protein in a highly controlled manner. The modifications are restricted to changing the amino acid sequence of a protein. There are alternative techniques to induce different modifications, but these are commonly not referred to as protein engineering. On the one hand, proteins are engineered with the goal of addressing fundamental questions such as the molecular basis for their functional properties; the consequences of amino acid substitution for folding, structure and conformational stability; the molecular basis for the spontaneous association of proteins into large protein assemblies and assembly-related properties. On the other hand, proteins are engineered with the practical objective of making improved proteins for existing applications or extending the functions of proteins towards new applications. In general, such protein engineering targets reflect the requirements for commercial application of proteins such as stability, enhanced affinity for cofactors and performance in the presence of strong solvents, highly reactive chemicals, hostile enzymes, at extreme temperatures, at extreme pH and so forth. For many potential bioconversions, the available enzymes need further optimization with respect to turnover rate, specificity, and sensitivity to inhibition. Medical applications require proteins that can escape the normal processes of elimination, do not trigger the immune system, are able to selectively enter cells and tissue, and exhibit activity and stability in the presence of enzymes and natural inhibitory factors.

After a decade of protein engineering, the technology has developed as a very useful analytical research tool to introduce subtle local perturbations in the structure that allow for analysis of structure-function relationship and sometimes lead to significant changes in the properties of proteins. Several examples also illustrate that the useful properties of a given enzyme can be improved. In the detergents market and in starch processing, a number of improved engineered enzymes have been successfully introduced. Examples in

which entirely new functions have been engineered into proteins, however, are rare. The modification of existing functions is probably easier to achieve, given the current limited understanding of protein structure-function relationships. In some cases it has been shown that the minimum size of a protein required for a specific function outside a living environment can be much smaller than in nature, because a major part of the amino sequence of natural proteins serves only for the survival of the protein inside the living organism. Once the minimal required tertiary fold for a certain function has been established, powerful computational design algorithms may screen an immense combinatorial library of sequences in order to pick out the sequence that fits best the desired structure. In fact, the first fully tailored protein using such an advanced computer model was realized only very recently [Dahiyat, 1997]. In addition, when such functional miniproteins approach the size at which they can be easily produced by chemical synthesis then a variety of non-proteinogenic aminoacids can be introduced. In this way such miniproteins can be a source of inspiration for the design of non-proteinogenic small molecule mimetics. Finally, the technique is interesting for nanotechnology because in principle it might provide a route to assemble artificial molecular machines based on these artificial proteins. It is clear that neither high-resolution three-dimensional structures nor theoretical methods alone can answer the question: which aminoacid substitutions should be made in order to obtain a desired function? It is even more difficult to estimate the magnitude of these effects. It is felt that our fundamental knowledge of proteins is still too limited to rely completely on rational design. Even in the absence of this technology, however, proteins can be altered for new functions and properties by random approaches. The construction, expression and isolation of mutants has become so efficient that in depth determination of structure-function relationships and theoretical prediction is much more elaborate than just making and testing the mutant(s). In concurrence with the trend of combinatorial chemistry, there is an ongoing tendency to find a particular structure by fully or partially random mutation and selection or screening among extremely large numbers of sequences [Kuchner, 1997]. These methodologies are called applied molecular evolution and are considered essential for the practical use of the new opportunities of protein engineering [Kauffman, 1992]. Major challenges in the future will be the further development of ways to explore the structure-function relationships that will allow for more efficient design of enzymes with desired properties.

4.12 NANODEVICES FROM PHOTOBIOLOGICAL MATERIALS

K.J. Hellingwerf¹⁹, J.J. van Thor¹⁹, W.D. Hoff²⁰ and J. Hendriks¹⁹

INTRODUCTION

Bacteriorhodopsin (BRh) was discovered in 1971 in the archaeobacterium *Halobacterium halobium*. Soon after this, various applications were proposed for this photoactive protein, based on its unique photobiological activities, function and stability. These proposals ranged from a desalination device for sea water, via the light-driven hydrolytic generation of hydrogen gas, to applications in optical and memory devices, like an artificial retina. All these applications are based on materials properties that are intrinsic to single molecules of bacteriorhodopsin, in particular the capacity to reversibly change its color and to transport protons (H^+) upon illumination. Since color changes can be detected optically, such devices are well-suited for miniaturization. During the past few years, the proposals for application of bacteriorhodopsin in information technology have been further advanced, in parallel with the construction of laboratory-scale prototypes of bacteriorhodopsin-based memory devices. Also, additional photoactive proteins with attractive features for advanced photo-physical applications have been discovered and characterized. Below we review these developments.

BACTERIORHODOPSIN

Structure and function

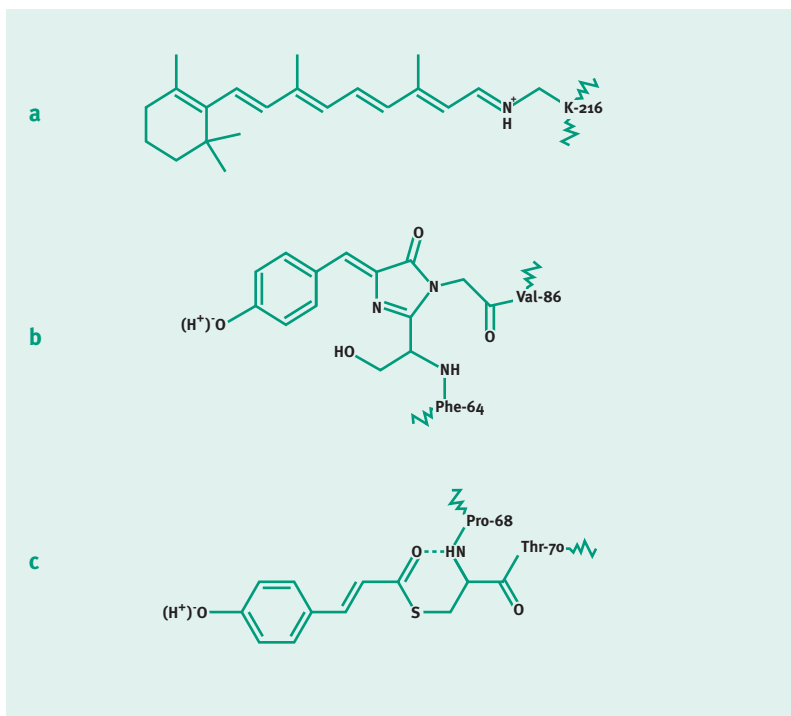
The conspicuous purple color of the cell membrane of *Halobacterium halobium* was the incentive for the detailed molecular characterization of bacteriorhodopsin. This protein is the only protein component in the ‘purple membrane’ sub-fraction of its cytoplasmic membrane [Oesterhelt, 1971]. Like eye-rhodopsin, the pigment responsible for the absorption of light in the rods and cones of the retina of the human eye, bacteriorhodopsin is a strongly absorbing dye. In both, the purple color is caused by a single characteristic group, the retinal chromophore (figure 4.12.1a on page 266) that is linked to the (bacterio)rhodopsin molecule through a covalent – so-called Schiff-base – linkage. The color of bacteriorhodopsin can temporarily be bleached by illumination, which is accompanied by transient release of a proton to the solution. Because release and uptake take place on the extra- and intra-cellular side of the protein, respectively, bacteriorhodopsin functions as a light-driven proton pump, thus providing the halobacterial cell with metabolic energy [Stoeckenius, 1982]. The protein part of bacteriorhodopsin is a biopolymer containing 224 aminoacids. These are arranged in 7 segments of α -helical structure, each spanning the cell membrane, with short connecting loops on the membrane surface (figure 4.12.2a on page 260).

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Figure 4.12.1

Structure of the characteristic group (chromophore) responsible for the color of: (a) bacteriorhodopsin (BRh), (b) green fluorescent protein (GFP) and (c) photoactive yellow protein (PYP).



The chromophore is situated in the middle of the membrane, surrounded by the alpha-helical segments. Light-absorption by the chromophore induces *cis/trans* isomerization and disruption of a hydrogen-bonding network. This induces a specific conformational change in the protein, which leads to the release of a proton to the extracellular medium. Subsequent rearrangements lead to the re-binding of a proton from the cytoplasm and to reformation of the hydrogen-bonding network, which completes the cycle. The short-lived transient states of the photocycle each have a distinct color. Their exact number and order of appearance (tentatively named K, L, M1, M2, N, and O) are not definitely settled yet.

Relevant materials properties

All published applications of bacteriorhodopsin molecules are based on one or more of the following specific features:

- The capacity to *transport a proton* upon illumination. This generates an electric potential when the protein is incorporated in a membrane, or in any form of material that forms a barrier towards proton diffusion. Surface charges are asymmetrically distributed over the two surfaces of the purple membrane. Deposition of these membranes on a support, in the presence of an electric field, allows a net-orientation of all molecules, and thus directionality of proton transfer.
- The capacity to *reversibly change its color*. This capacity is very diverse. The initial color change to red takes place within a few picoseconds. After milli-

seconds, a yellow intermediate is formed (M), which relaxes to the last transient intermediate of the photocycle (O). In partially dehydrated films of bacteriorhodopsin, the O-intermediate accumulates. If it absorbs a second photon before relaxation to the ground state can occur, an extremely long-lived yellow intermediate is formed that is very useful for application as a bistable optical switch [Popp, 1993]. The speed of some of the slower transitions between these transient states is sensitive to various external conditions such as temperature, electric field strength and humidity. These external parameters thus allow one to modulate the distribution of bacteriorhodopsin molecules over these states.

- Its extraordinary *stability*. This is particularly true for the chemical environment in many of the proposed devices, where proteolytic enzymes (enzymes catalyzing the breakdown of proteins) have little chance to degrade bacteriorhodopsin. The resistance against elevated temperatures and extremes of pH and salt concentration is far above average for a membrane protein. This is partially caused by the arrangement of bacteriorhodopsin molecules in two-dimensional crystals. The photochemical stability of bacteriorhodopsin is also extraordinary [Oesterhelt, 1991; Chizhov, 1992]. Optical switching of organic and inorganic photoactive materials typically is limited to less than a thousand times. In bacteriorhodopsin, as many as one million switching events cause only minimal damage, provided that it is excited on the red side of its main absorption band. The photochemical stability of photoactive yellow protein (see below) is comparable to that of bacteriorhodopsin [W.D. Hoff and K.J. Hellingwerf, unpublished]. A condition that must be controlled stringently is the humidity, because photoactive proteins generally show no photoactivity below threshold values of humidity.

For specific purposes, the properties of bacteriorhodopsin can be adjusted in different ways. First, specific aminoacid side chains of the bacteriorhodopsin molecule can be modified using recombinant-DNA techniques. Second, the bacteriorhodopsin chromophore can be replaced *in vitro* by other chromophores. Through both approaches several variants of bacteriorhodopsin have been made, showing improved performance [e.g. Popp, 1993]. Thirdly, general chemical modification of the protein is also possible.

NEWLY DISCOVERED PHOTOACTIVE PROTEINS

During the past five years a number of recently discovered photoactive proteins have been characterized in detail. Of these, particularly green fluorescent protein (GFP) and photoactive yellow protein (PYP) have considerable potential for application in optical devices [Hellingwerf, 1996]. Their properties will therefore briefly be described below.

Green fluorescent protein

Green fluorescent proteins (GFPs) are found in a number of jellyfish species. Although the spectral properties of these proteins differ slightly, their chromophore is identical (figure 4.12.1b). The main body of literature on green fluorescent protein deals with its use as an *in vivo* marker for gene expression and subcellular localization. Nevertheless, their structural and photophysical properties have been studied as well. Recent experiments have shown that green fluorescent protein can be classified as a photoactive protein with a very complex photocycle that involves at least six intermediate (neutral and ionic) states. Green fluorescent protein is brightly fluorescent and shows an unusual biochemical resistance towards proteases and high thermal stability [Chattoraj, 1996]. Variants of green fluorescent protein with optimized absorption and fluorescence characteristics have been produced by genetic engineering. Single molecules of green fluorescent protein can be used as optical switches [Dickson, 1997]. By imaging fluorescence of single molecules via confocal microscopy, a 'blinking' behavior of individual green fluorescent protein molecules was observed (compare section 5.4.2). This means that they switch between fluorescent and non-fluorescent states at the seconds timescale, i.e. that they are photoactive. This switching behavior would never have been observed in 'bulk' samples in which the properties of individual molecules are averaged. In addition, in the fluorescent state GFP can be switched between forms in which its chromophore is in the neutral or in the anionic state. These characteristics open up exciting possibilities for use of green fluorescent protein in information storage and retrieval, although further characterization of the states involved will be necessary.

Photoactive yellow protein

Photoactive yellow protein (PYP) was discovered in 1985 among the colored proteins from the extremophilic bacterium *Ectothiorhodospira halophila* [Meyer, 1985]. It functions as a photoreceptor for phototaxis [Sprenger, 1993], the process that elicits net migration of individual bacteria in response to the intensity and/or color of illumination. It is a water-soluble protein, which is an attractive feature for application as a nonlinear optical material because it allows one to make a clear solution rather than a light-scattering suspension. Photoactive yellow protein has been characterized in detail. Its chemical [Hoff, 1994] as well as three-dimensional structure (figure 4.12.2c on page 260) has been resolved [Borgstahl, 1995]. After absorption of a blue photon, the yellow protein enters a photocycle that resembles bacteriorhodopsin's, although its chromophore is *p*-coumaric acid (figure 4.12.1c). When the negatively charged chromophore of the ground state of the protein absorbs a photon, it isomerizes and temporarily acquires a proton [Kort, 1996]. It is still unclear whether this proton is donated by the protein or taken up from the solution. Also unsettled is

the question of the magnitude of the conformational change that is necessary to form the late, blue-shifted, photocycle intermediate of photoactive yellow protein [compare Genick, 1997; van Brederode, 1996]. The ground state of photoactive yellow protein is recovered after re-isomerization and deprotonation of the chromophore and relaxation of the conformational changes in the surrounding protein; it remains to be established whether these partial reactions proceed independently or in one concerted reaction. The detailed characterization of the spatial structure of the blue-shifted intermediate, which presumably also is the signaling state of this photoreceptor, forms a major challenge for future research.

Comparison of the three proteins

Each of the three proteins discussed in this contribution has its specific pro's and con's. Bacteriorhodopsin has the nice feature of generating voltage pulses, particularly when the purple membrane fragments are properly aligned. Green fluorescent protein has very bright fluorescence. The magnitude of the conformational transition in the photocycle of photoactive yellow protein may imply that significant volume changes are elicited upon illumination, a feature that may be exploited in future devices. Furthermore, the use of chromophore analogs allows one to make derivatives of bacteriorhodopsin and photoactive yellow protein that are highly fluorescent [Kroon, 1996].

PROPOSALS FOR APPLICATION

Early proposals for bacteriorhodopsin

The proton-pumping function of bacteriorhodopsin was initially used to prove that biological energy transduction is based on the reversible transport of protons through the cell membrane [Racker, 1974]. Because bacteriorhodopsin is a light-driven proton pump and thus a biomolecular voltage generator [e.g. Hellingwerf, 1979], several early proposals for the application of this protein were made, often in the form of patents [Ohyama, 1991] and in part inspired by the first global oil-crisis, on the topic of light-induced generation of ATP (adenosine triphosphate) or current. More remote proposals were the assistance in liberating hydrogen gas from water, or even in the desalination of sea water [for a review see Oesterhelt, 1991]. The similarity between bacteriorhodopsin and rhodopsin also led to the development of films of bacteriorhodopsin that mimic the retina in artificial photoreceptor devices [Miyasaka, 1992].

Memory and processing devices

A large number of proposals for application of bacteriorhodopsin of more recent date are based on the use of the color-switching properties of the pigment for advanced optical processing techniques. In these proposals, bacteriorhodopsin is used either as a spatial light modulator or for information storage techniques. Spatial light modulators exploit the dynamics of the photocycle for optical signal processing purposes. Information storage techniques use bacteriorhodopsin for information storage through spatial or holographic data storage. Both types of application are discussed below.

Spatial light modulators (SLMs)

Spatial light modulators are integral components of a one- or two-dimensional optical processing device. These devices modify one or more properties of an incoming light signal, such as the intensity or the polarization. The modification can be controlled by applying electrical or secondary optical signals to the device. Bacteriorhodopsin films can be used in spatial light modulators using holographic, thresholding, or voltage control.

In *holographic* spatial light modulators, the film serves as a temporary storage medium for holograms, i.e. diffraction patterns from which the original optical field distribution can later be reconstructed by illuminating the film with a second laser. Reading with infrared light leaves the pattern intact, so that the hologram can be read many times. Recent applications of spatial light modulators include real-time pattern recognition and associative Fourier memories (see below).

In *thresholding* spatial light modulators, a nonlinear response to illumination produces two basic logical functions: AND and NAND. The outcome of the AND function equals zero (no light transmission), unless both incoming signals equal one (light transmission), whereas the NAND function yields one unless both incoming signals equal one. Combining both functions allows one to construct all logical functions, a *sine qua non* for computing. An ideal thresholding device has a transmittance of near zero below the threshold level and near 100% above the threshold level. The bacteriorhodopsin device uses the fact that it is a saturable absorber. If locally all dye molecules are excited, the dye is effectively bleached and all the excess light is transmitted. The thresholding spatial light modulator can be used in Fourier pattern recognition and optical associative memories (see below) to improve signal to noise ratios.

Both holographic and thresholding spatial light modulators can be *voltage-controlled* [Birge, 1992]. Voltage-control is used when a variable lifetime for the intermediate state is required. The thermal recovery lifetime of the M-intermediate can be modulated by applying an electric field across a film with oriented purple membrane fragments.

Information storage

Bacteriorhodopsin can be used in several types of information storage devices. The most important ones are the Fourier transform holographic (FTH) associative memories and three-dimensional optical memories. The former devices take an input data block (or: 'image') and scan the entire memory for the data block that matches this input. This operation is carried out independently of the central processor, thus allowing parallel computing. It then returns the data that most closely match the input data [Birge, 1992]. This type of memory may turn out to be a key in achieving artificial intelligence, since it works similarly to the human brain.

In three-dimensional optical memories, cubes containing a suspension of bacteriorhodopsin molecules are fixed in transparent plastic. In many applications, a magnetic field is applied during fixation to orient the bacteriorhodopsin molecules in space. To store data, two lasers with well-chosen wavelengths, and operating at right angles with respect to each other, are used to illuminate a specific part of the cube. Only in the region that is irradiated by the two lasers simultaneously, will bacteriorhodopsin enter its photocycle, so that within a few milliseconds the transient intermediate O is formed. Data can then be written to this activated region with a red laser, which excites the activated molecules into the state Q. In a sufficiently dilute solution, only a single molecule will be addressed. The Q state has a lifetime of several years. To read data from the cube, a region is again activated with the two lasers and then read with a low-intensity laser of a shorter wavelength [Birge, 1995]. A practical prototype of a three-dimensional memory based on bacteriorhodopsin has been realized by orienting the proteins molecules with an electric field, after which they were immobilized by polymerizing the solvent into a polyacrylamide matrix [Chen, 1995].

The storage density of a light-addressable memory device based on the characteristics of single molecules is ultimately limited by the size of those molecules, which is approximately 15 x 25 x 40 nm. The characteristics of green fluorescent protein suggest that indeed the storage of information in a single molecule may be within reach. However, to allow proper addressing of separate molecules inside a two- or three-dimensional high-density array of such single-molecule memory units, their mutual distance must be increased with respect to the closest packing possible. The maximum storage density is therefore inversely related to the reliability of the memory output.

A three-dimensional high-density array can only be addressed with far-field optics (section 5.4.1). The resolution of addressing of bacteriorhodopsin molecules is then restricted by the diffraction limit of the light of the wavelength selected. For the near-infrared light used for the excitation of bacteriorhodopsin and using conventional optics, this allows a resolution of approximately 300 nm in water, plastic or glass. The application of advanced optics such as the 4π -micro-

scope (section 5.4.1) could in principle improve on this until a theoretical maximum of approximately 100 nm. This would – if only just – justify the name ‘nano-device’. It would allow for a storage density of 10^{10} bits/cm² and 10^{15} bits/cm³, respectively. The use of shorter wavelengths to excite green fluorescent protein and photoactive yellow protein might increase these densities even further. Currently achievable information storage densities for bacteriorhodopsin-based devices with conventional optics are much lower, 1 Mbit/cm² and 10 Gbit/cm³. Nevertheless, it has been estimated that three-dimensional bio-optical memories with about a 300-fold improvement in storage capacity over two-dimensional devices can be realized, while both compare favorably with current silicon-based devices. In addition, three-dimensional optical memories provide the opportunity of parallel data processing. The field of designing new methods for data retrieval from bacteriorhodopsin-based devices is still in a state of rapid development [Birge, 1994]. Besides storage density, the access time of the stored information is an important parameter. The picosecond time scale of the initial (optical and electrical) reactions of bacteriorhodopsin makes it a very attractive material for read/write operations [Trissl, 1990]. One great challenge is the synthesis of truly functional nanostructures. An even greater challenge is the ‘communication’ with such a nanostructure. For applications of bottom-up nanotechnology, this is difficult because of its nanometer dimensions. Nevertheless, it has already been demonstrated that photocycle signals from (aggregates of) bacteriorhodopsin molecules can be communicated to the external world, using the lever of an atomic force microscope, with microsecond time resolution [Rouso, 1997]. Further work along such lines may lead to the development of exciting new devices.

4.13 THE EARLY EVENTS IN PHOTOSYNTHESIS

*R. van Grondelle*²¹

Introduction

Finding power generators for nanoscale machines presents a major scientific challenge. Nature has solved this problem by photosynthesis, a process that efficiently converts solar energy into a form that can be used by living organisms at the (sub)cellular level. Yearly about eight times the world’s energy consumption is fixed as high-energy carbohydrates. The study of the natural photosynthesis process also brings the possibility of learning to design and construct future bio-organic solar cells.

Photosynthetic organisms have found a unique solution for capturing the solar energy. Two ultrafast processes are the key steps: excitation energy transfer in the *light-harvesting antenna* and electron transfer in the *reaction center* (RC). A solar photon is absorbed by a photosensitive pigment. This can be chlorophyll

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in plants and algae, bacteriochlorophyll in bacteria, or carotene-like pigments that are present in either one of these species. The energy is rapidly transferred from the excited pigment molecule to and between many other pigments, until it is trapped by a reaction center. There, an ultrafast electron transfer converts the excitation energy into a stable charge separation. Since the fast electron transfer occurs across a membrane, an electrochemical gradient is formed. This gradient is fundamental to all energy conversions of living organisms. More than 95% of absorbed photons are delivered to the reaction center. The photosynthetic apparatus that mediates the highly efficient transfer processes consists of a membrane-associated network of interconnected proteins that holds pigment molecules in an ordered state. In plants, two reaction centers (photosystems 1 and 2) operate in series, each with its own light-harvesting system. Photosystem 1 donates an electron to an electron carrier. The electrochemical potential generated by photosystem 2 is strong enough to extract electrons from water, thereby producing oxygen. Photosynthetic bacteria make do with one reaction center, but they can not use water as a source of electrons. In this contribution, some recently discovered structures of photosynthetic pigment proteins will be discussed. These nanostructures carry out the initial steps of photosynthesis. New techniques in ultrafast laser spectroscopy and genetic engineering help to understand how.

The light-harvesting antenna

The reaction centers of bacteria and plants are highly optimized devices that would be difficult to improve. However, on their own they would be of limited significance to the plant or bacterium. The energy provided by the sun is too low to justify the efforts a cell must take for their synthesis. However, in nature the reaction centers are surrounded by a light-harvesting antenna (LHA). This antenna generally consists of (bacterio-)chlorophyll and carotenoid molecules that are complexed to special, often membrane-bound, proteins. Photons are absorbed by the antenna. The excitation is efficiently transferred to the reaction center where a charge separation is initiated. The light-harvesting antenna greatly increases the absorption cross section of each reaction center and makes optimal use of their energy-converting capacity.

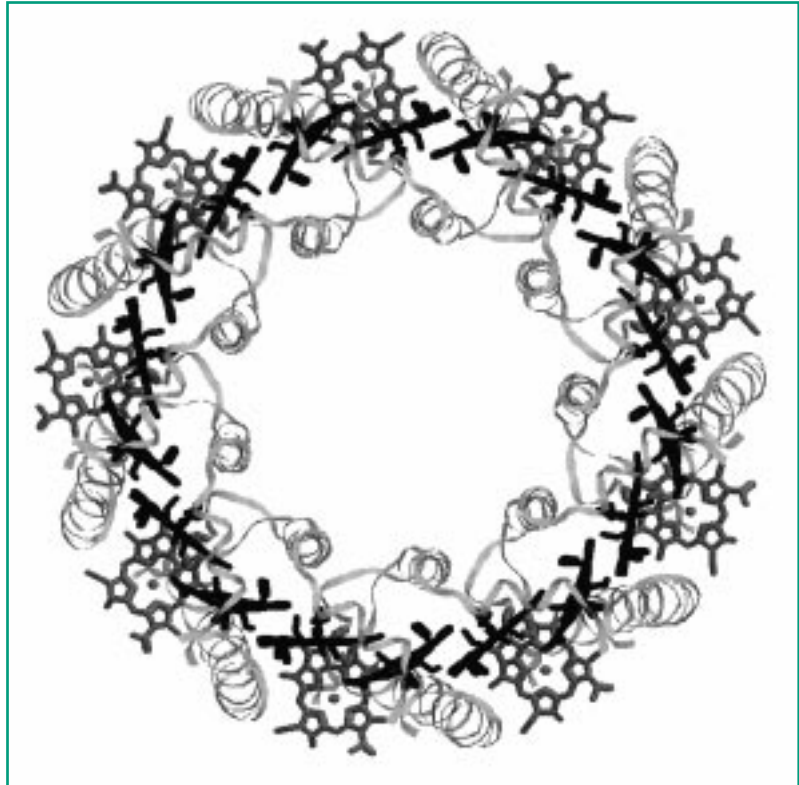
Recently the three-dimensional structures of two light-harvesting complexes have been resolved. One of them is an abundant plant protein (LHC2) responsible for binding about 50% of all chlorophyll on the planet [Kühlbrandt, 1994]. The elementary unit of the complex is a polypeptide binding 12 chlorophyll pigments. The pigments are arranged in two layers. Their mutual distances are of the order of 1 nm or less allowing for ultrafast excitation transfer.

The structure of a bacterial light-harvesting complex is shown in figure 4.13.1 (on page 274). This structure contains 18 strongly coupled chlorophyll molecules bound in pairs to 9 polypeptide dimers arranged in a symmetrical ring.

The non-covalently bound chlorophyll is collectively responsible for strong absorption of infrared light, which has wavelengths much longer than light absorbed by free chlorophyll. Within each pair, the chlorophyll molecules have a Van der Waals interaction, while the dimer-dimer distance in the ring is about 1.7 nm. This complex also contains 9 weakly interacting chlorophyll molecules that lie close to the surface and absorb in the infrared.

Figure 4.13.1

*Top view of the structure of the peripheral light-harvesting complex (LH2) of the bacterium *Rhodospseudomonas acidophila*. The nine polypeptides constituting the inner ring of helices are of the alpha-type, the nine polypeptides forming the outer ring are of the beta-type. Eighteen bacteriochlorophylls absorbing light with a wavelength of 850 nm (black) are sandwiched between the two concentric polypeptide rings. Their planar structure is perpendicular to the plane of the LH2 ring. Nine bacteriochlorophylls absorbing light with a wavelength of 800 nm (dark grey) are positioned between the helices and have their planes almost parallel to the membrane plane. Reprinted with permission from Nature [McDermott, 1995]. Copyright 1995 Macmillan Magazines Limited.*



Experiments have shown that the energy transfer among all the pigments in this complex takes place in less than a picosecond [Visser, 1995]. The complex is excited with an ultrashort laser pulse at the high-energy side of the major absorption band. Within 0.2 ps (1 picosecond = 10^{-12} s) after the excitation, the absorption profile changes due to energy transfer between pigments within the ring that are absorbing at slightly different wavelengths. In less than a picosecond an equilibrium distribution is reached. This experiment demonstrates the ultrafast energy transfer that in fact causes this spectral equilibration. In a living bacterium, the excitation hops from ring to ring on a timescale of about a few picoseconds. Eventually, the pigments of the light-harvesting antenna neighboring the reaction center are reached and the excitation energy is transferred to one of the reaction center pigments.

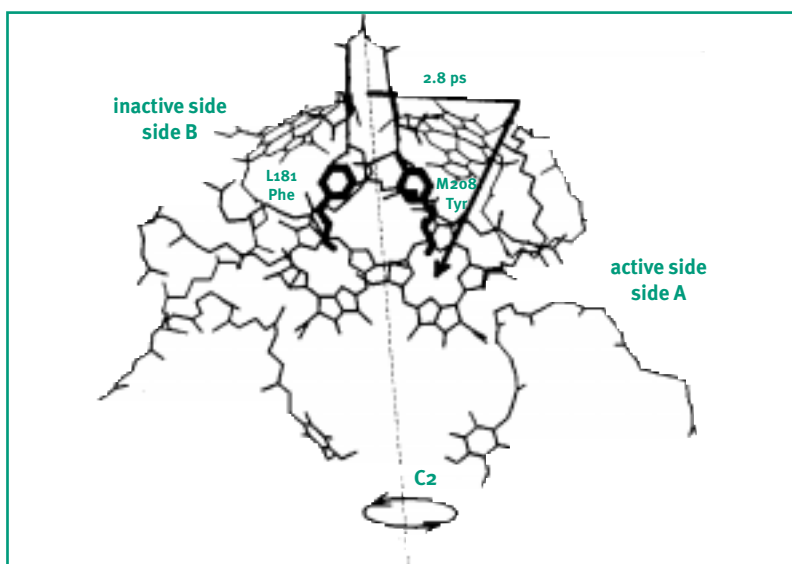
The reaction center of photosynthesis

Rhodospseudomonas viridis

A great deal of progress has been made in understanding the function of the reaction centers since the structure of the reaction center of the photosynthetic bacterium *Rhodospseudomonas viridis* was resolved with atomic resolution [Deisenhofer, 1993]. The core of the reaction center is made of two very similar membrane proteins, while a third polypeptide covers the reaction center surface. Both membrane proteins possess five membrane-spanning helices forming a cage around the eight molecules active in the photosynthesis process (figure 4.13.2). The centrally located 'special pair' of bacteriochlorophyll molecules is excited by absorption of a photon. Within picoseconds, charge separation occurs.

Figure 4.13.2

Pigment organization in the bacterial photosynthetic reaction center of *Rhodospseudomonas viridis* with the central bacteriochlorophyll 'special pair', separate bacteriochlorophyll molecules, and two types of electron carrier molecules. These molecules are non-covalently bound to the reaction center. The reaction center shows a remarkable symmetry with the pigments arranged in two branches, indexed A ('active') and B ('inactive'). Surprisingly, electron transfer occurs only along the active branch. In addition two important amino acids are indicated, phenylalanine at position L181 and a tyrosine residue at position M208. The hooked arrow indicates the path of electron transfer along the active branch.



The special pair becomes positively charged while the electron hops to an electron carrier molecule. The electron is transferred to a second and then to a third carrier. The special pair is restored to neutrality by electron transfer from another electron carrying protein (cytochrome). This sequence of reactions is repeated after the absorption of a second photon. After this, a doubly charged electron carrier molecule (Q_A) leaves the reaction center, creating an electrochemical gradient across the membrane in which the reaction center is located. The whole process takes place within hundreds of *milliseconds*.

Why electron transfer essentially occurs only along the active branch is not fully understood. Theoretical estimates of the transfer along both paths do indeed favor the active branch, but not in the experimentally observed ratio. One conspicuous structural difference between the branches is that they contain a

different aminoacid molecule at specific positions (figure 4.13.2). The introduction of mutations at these positions does not lead to activity in the inactive branch, but induce dramatic changes in the rate of charge separation [Fleming, 1994]. These changes were ascribed to changes in the free energy of the initial radical pair (the positively charged special pair and the first electron carrier) due to the mutation. The observations suggested that the changes in the protein structure at the moment of electron transfer are very small, so that structural changes cannot help to explain the electron transfer asymmetry between the branches either. More recent experiments suggest the involvement of a charge transfer state within the bacteriochlorophyll special pair before electron transfer occurs. A measurable amount of negatively charged bacteriochlorophyll in the inactive branch was detected in a double mutant. The asymmetric electron transfer may very well involve many aminoacids in the structure of the reaction center, resulting in a higher effective dielectric constant along the active branch [Heller, 1995; Steffen, 1994].

Green plants

The reaction center of photosystem 2 of green plants shows a remarkable similarity with the bacterial reaction center. Only a few years ago the reaction center of photosystem 2 was obtained in a purified form that demonstrates photoactivity (i.e., it is able to respond to light photoelectrically or by chemical reaction). The core of the reaction center binds four chlorophylls and two electron transfer molecules. They are probably arranged as indicated in figure 4.13.2, except for the special pair that seems to be more weakly coupled. The reaction center contains two additional chlorophylls located at its periphery. The rate of the initial charge separation appears to be similar to that of the bacterial reaction center.

The reaction center of photosystem 1 is totally different. In its minimal form it is a dimer consisting of two covalently bound similar polypeptides. It binds close to one hundred chlorophyll molecules. Structural analysis has revealed many helices across the membrane and suggests that the chlorophylls and other cofactors involved in primary electron transfer are again arranged in two symmetric branches [Krauß, 1996]. The reaction center found in both green sulfur bacteria and the recently discovered heliobacteria is related to photosystem 1, with the unique additional feature that the reaction center is truly symmetric.

Energy transfer

In bacteria the light-harvesting antenna surrounding the reaction center is also arranged in a highly symmetry ring-like structure. Energy transfer along the ring proceeds in less than a picosecond, while transfer to the reaction center lasts tens of picoseconds. The latter process may well be the rate-limiting step in the sequence of primary events. The role of the bacteriochlorophyll molecule in the

active chain has been debated since the reaction center structure became available. Today most scientists believe that the molecule is transiently observable as an electron transfer intermediate, with the rate at which the electron arrives from the excited special pair almost four times slower than the transfer away to the next electron carrier. It is generally assumed that the excitation transfer takes place by the incoherent hopping of fully localized excitations. However, the available structural data suggest that the electronic couplings between the bacteriochlorophyll molecules in figure 4.13.2 are sufficient to delocalize the excitation. The bacteriochlorophyll molecule in the active branch then functions to couple the electronic states of the bacteriochlorophyll special pair and the first electron carrier molecule. The decay of the coherence of the initially excited state and the interaction of the delocalized excited electron with low frequency vibrations of the surrounding protein medium will be crucial parameters in the description of the dynamics of excitation transfer. However, a theory incorporating these elements is not available. Finally, much remains to be learned about the influence of temperature on the electron transfer. The primary electron transfer events actually speed up as the temperature is reduced to low temperatures.

Conclusion

Photosynthesis is a highly sophisticated process to store and convert solar energy for living organisms. Understanding it fully may lead to the development of bio-organic solar cells producing electricity in addition to the organic and inorganic cells discussed in section 4.9. In the future, they may become of use for empowering nanomolecular machines. However, before application in such devices can be realized, considerable scientific and technological advances are needed.

4.14 DNA NANOSTRUCTURES

A. ten Wolde

This contribution is primarily based on the master thesis of W.J.W. Tepper, which was approved by G.T. Robillard, University of Groningen [Tepper, 1997].

Over the last few years, DNA molecules have received much attention as a potential structural component for nanotechnology, in particular for nanoelectronics. DNA molecules have several advantages over proteins:

- DNA molecules with a predefined sequence can be chemically synthesized and biochemically reproduced;
- the simple rules of base-pairing allow programming of the intermolecular associations;

- nature provides many structural varieties of DNA, some of which form an excellent basis for synthetic structures;
- double string fragments 5 to 7 nm long have a high structural rigidity;
- two pieces of DNA can be joined covalently to form a single double helix by using the proper enzymes and cofactors.

A beautiful example of their ability to establish a self-assembling electronic connection was already presented in section 1.2. Another type of application, especially pursued by Nadrian Seeman²² and his colleagues at New York University, is the use of a structural DNA network as an assembly system for large supramolecular structures. They have been able to synthesize a large variety of artificial DNA nanostructures, including:

- branched DNA structures;
- immobilized DNA branching points with 3, 4, 5 or 6 arms;
- complex DNA assemblies by specific coupling of different DNA fragments using ‘sticky ends’;
- a DNA-square;
- a DNA cube (figure 4.14.1 on page 260);
- a DNA octahedron;
- DNA periodic networks, such as two-dimensional lattices.

Experimental determination of the three-dimensional structures has proven difficult. This is partly because they can only be synthesized in small quantities, but the samples probably also contain a mixture of several conformational varieties of the desired structure.

4.15 PROSPECTS FOR APPLICATIONS

A. ten Wolde

Medical applications

One of the most difficult challenges pharmaceutical companies face in the next decade is successful *drug delivery*. Nanosized vesicles such as liposomes (section 4.6), dendrimers (section 4.7), and possibly also modified fullerenes are excellent candidates for the efficient delivery of proteins, peptides, and oligonucleotides to their desired site of action. Critical factors for successful application of these vehicles include stability of the drug in the vehicle during manufacture and subsequent release in the body, stability of the vehicle upon storage, and the ability to perform aseptic manufacturing of the vehicle.

Commercialization is nearing completion for peptides and will occur for proteins in the next two years, assuming the success of the current clinical programs [McClelland, 1997].

22 <http://seemanlab4.chem.nyu.edu/homepage.html>

Nanotapes, molecular tapes formed by self-assembling oligomers, “could be cast into tiny tubes and replacement arteries and blood vessels. The sticky outer surface would bind itself to muscles and other tissues, while the smooth, hydrophobic inside would prevent blood clotting as it passes through” [Stupp, 1996].

(Opto)electronic devices

Molecular sensors are being developed that can detect nanomolar concentrations of substances because a single protein pore produces a measurable signal. There is a pressing need for such sensors. In addition to the example presented in section 1.2, the Australian Membrane and Biotechnology Research Institute (AMBRI²⁴) has built a similar biosensor – the ICS Biosensor – based on ‘novel nanosized components’. Molecular sensors are not only highly sensitive, but also very rapid, small, biocompatible, they have a high gain, and they can mimic the functional properties of a biological membrane.

Biochip arrays, already produced commercially, are a product of microsystem technology and biotechnology (section 1.2). Ongoing miniaturization can be expected push them into the nanoregime within twenty years, and can eventually lead to devices with arrays of individual bio-organic or organic molecules, each producing a measurable signal when their unique ‘counterpart’ substance binds to them. The analytic power of such devices can hardly be overestimated. *Plastic electronics* involves the use of organic conductors and semiconductors. Conducting polymers are already being applied in batteries and in antistatic coatings. Philips is working seriously on the development of plastic chips. Their main advantages are their easy processing and their flexibility. Plastic light-emitting diodes and disposable electronics such as chip cards and identification tags are under development. In the mid-term, semiconducting organic molecules as discussed in section 4.8 are candidates for application in plastic electronic devices. The same holds for molecular *solar cells* as discussed in section 4.9. Maybe conducting dendrimers will find some electronic application as well. On an even longer term, a better understanding of photosynthesis might enable the fabrication of bio-organic solar cells using or imitating photosynthesis, but this is speculation at this time.

Molecular optical devices are another line of research. Chiral optical molecular switches (figure 4.2.9) as host compounds of liquid crystalline (LC) matrices can be applied in flat displays. Liquid crystalline dendrimers might find similar applications. Photosensitive proteins such as bacteriorhodopsin are being investigated with the aim of developing high-density memory and ultrafast processing devices (section 4.12). Photoswitchable molecular wires (figure 4.2.4b) and similar nanostructures may find applications for optoelectronics as well.

Molecular processors and memories have potential for the longer term. It has been demonstrated that the rules of DNA self-assembly, coupled with the poly-

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merase chain reaction (PCR) amplification of DNA, can be used to solve a really difficult mathematical problem [Adeleman, 1994]. However, at present this method is not very practical. An approach getting more attention uses the fact that many biological and organic macromolecules are bistable, meaning that they can alternate between two states in which they are stable (figures 4.2.6, 4.2.4.b, and 4.2.9). Supramolecular bistable systems have been engineered by filling a molecular capsule as depicted in figure 4.3.5 with a small dipole molecule (figure 4.3.7). However, before such a system can function in an operational molecular circuit or memory, the state of each switch must be individually addressable, i.e. controllable by an external influence and also detectable. For the industry, the addressing has to be a fast and reliable way as well. These are major issues in current research. Other important questions for the development of molecular chips are: how should the structure be assembled? How can it be powered? How can the clock signal be generated? How will the individual components be interconnected? How can defects be traced and repaired? How can the molecular world be connected to the macroscopic world? Years of intensive research will be necessary to address these.

However, provided that these problems are tackled, molecular nanotechnology will undoubtedly lead to new electronic devices. The development of an intelligent biosensor will be an important step forward, as is the recent development of procedures to deposit self-assembling protein and lipid films of one or several monolayers thick, with a high structural, thermal and functional stability [Nicolini, 1995 and 1997]. Another encouraging result with respect to the thermal stability of biological materials was the recent design and synthesis, by Dutch scientists from Groningen, of a modified protein that remains intact and functioning for over one hour at 100°C [van den Burg, 1998].

New materials

As stated in chapter 3, molecular nanotechnology provides a way to further increase control over material properties. This means that in the long term, molecular nanotechnology will find applications in all the areas mentioned there, such as optics, energy, automobiles, cutting tools, the aerospace and building industry, and the military.

Fullerenes may serve as an early example. This newly discovered class of three-dimensional carbon structures (bucky balls, tubes and varieties thereof) have to some extent been a symbol for molecular nanotechnology. The fact that they have not been separately treated here may be a sign that their novelty wears off. However, it should be mentioned that they are finding applications in many areas, including photoresists, microelectronics, catalysts, superconductors, drug delivery, nanosized test tubes, molecular filters, sensors, batteries and solar cells (section 4.9), while they may become important for the development of molecular electronics (section 2.6) [Eickenbusch, 1993]. To mention just one

example: a company in Cambridge, MA, adds small amounts of nanotubes to plastic to make it electrically conductive; these plastics are used by the automotive industry to make parts that are coated with charged droplets of paint [Browne, 1998].

Catalytic materials form another opportunity. Some dendrimers have shown catalytic activity. In addition, catalytic antibodies, amorphous organic polymers and metal oxides, and zeolites, have been prepared using organic molecules to direct their synthesis. Research indicates that these catalysts may be rationally designed by ‘molecular imprinting’, meaning that they are prepared via the use of rationally constructed organic templates that mimic reaction transition-states [Davis, 1997].

Molecular machines

Molecular motors exist in nature and are under intensive study. In the long term it may very well be possible to design and synthesize modified or even artificial molecular motors. The same can be said about *molecular assemblers*. Some of the catalysts used in today’s chemistry can already be viewed as basic versions of molecular assemblers; in the future it may be possible to produce artificial analogs of the ribosome. As discussed in section 1.1, the scenarios of futurologists such as Drexler and Merkle assume that this will in fact prove possible and will deeply affect our society because it revolutionizes manufacturing; however, scientifically speaking, this is still pure speculation.

4.16 FUTURE PROSPECTS

G.T. Robillard²⁵ and A. ten Wolde

Molecular nanotechnology is expected to become a key technology for the 21st century. However, it is still in its infancy, and is still far more of a science than a technology. Therefore, it is important to avoid generating unrealistic expectations. The development of molecular nanotechnology will depend on physicists, chemists and biologists cooperating in cross-disciplinary research, the expectation being that molecular nanotechnology will emerge precisely at the interface of these three disciplines.

Molecular nanotechnology can be viewed as a growing toolbox of (bio)chemical techniques for rational design, synthesis and engineering. This toolbox will be used to tailor the structure and properties of all kinds of molecules with respect to desirable functions such as self-replication, self-assembly, self-organization, defined activities and affinities, and responsiveness to the environment. Subsequently, these molecules will be used as building blocks for the construction of supra- and macromolecular structures. Some of the key steps that will have to be taken in the realization of this technology are:

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- An understanding of energy transport by electronic excitations and the role of environment on transport properties at the nanometer scale
- The development of novel concepts to understand charge carriers and their intermolecular transport including charge recombination, traps and interfaces
- The construction of nanostructures for the conversion of light into electrical or chemical energy or vice versa
- The development of optical methods to address single molecules
- The construction of novel molecules and nanoscale structures with interesting properties for electronically functioning devices
- The development of methods to integrate functions from organic, bio-organic, and inorganic semiconducting and conducting materials into devices of nanometer dimensions
- The development of computational methods for calculating the structure and dynamics of (macro)molecules and complexes
- The development of methods to assemble address molecules to – and assemble them at specific coordinates
- To develop molecular components capable of executing movement – expansion, contraction, linear directional movement and circular movement – under the control of external stimuli.

Near-term opportunities can be found in the intermediate area of combining molecular materials and molecular organizational concepts into devices that are larger than nanometer dimensions but which rely on precise nanometer-scale organization for their function. These include devices such as organic-based solar cells, light-emitting diodes (LEDs), biosensors and sensor technology in general. While molecular nanotechnology cannot yet boast of major applications, several areas where important applications can be expected within the next ten or twenty years have been pinpointed in section 4.15.

In view of the importance of molecular nanotechnology as a key technology for the 21st century (section 1.1), we recommend that both governments and industries invest in long-term research in the component disciplines that form the foundation of this fascinating, promising field.

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5

Nanoscale-resolution microscopes

5.1 INTRODUCTION

A. ten Wolde

This chapter explains the fascinating imaging possibilities of scanning probe microscopy and of nanoscale-resolution optical microscopy. When you think about it, ‘*nanoscale-resolution microscopes*’ is not an elegant expression. ‘*Nanoscopes*’ would actually be a much better term. After all, the essence of this new class of tools for measurement and analysis of the ultrasmall is that they can image with a resolution ten times below the microscale. However, this term can not be used as a generic name because NanoScope is the registered trademark of a specific product line of Digital Instruments, one of the main scanning probe manufacturers.

It should be noted that besides scanning probes, various other techniques are becoming very powerful and important as well, especially for the imaging of three-dimensional structures. For instance, the possibilities of NMR (nuclear magnetic resonance) spectroscopy and x-ray crystallography for the analysis of the molecular structure of biomacromolecules are discussed in section 4.11. Neutron diffraction is also used for this purpose. High-resolution electron microscopy (HREM) is important for analyzing nanoparticles, nanostructured materials and patterned surfaces (section 3.6) as well as *in vitro* biological samples (section 4.6). Rutherford backscattering (RBS), elastic recoil detection (ERD) and x-ray photon scattering (XPS) are powerful tools for the study of interfaces.

The focus on scanning probe microscopy and nanoscale-resolution optical microscopy has been chosen because these techniques combine the possibility for measurement with that of manipulation. This makes them more versatile as tools for nanotechnology than other techniques. Although recently discovered (section 5.2.1), a variety of scanning probe microscopes has already been developed (table 5.1.1). In addition, some of the techniques discussed do not require complicated sample preparation. For instance, the ability to work on *in vivo* substrates and determine structure-function relationships is the main reason for the popularity of atomic force microscopes (AFM) with biologists. Finally, this chapter focuses on imaging: the use of scanning probes for fabrication by the manipulation of atoms and molecules is discussed in section 2.2.4.

5.2 SCANNING TUNNELING MICROSCOPY

J.W.M. Frenken^{1,2}

5.2.1 PRINCIPLE OF OPERATION

The scanning tunneling microscope (STM) is a relatively new type of high-resolution microscope that has initiated a revolution in solid-state physics as well as other research fields. It images the surfaces of conductive materials with atomic resolution, and thus provides a direct view of the ‘nanoworld’. Since its invention in 1981, the scanning tunneling microscope has quickly found its way into both academic and industrial research laboratories, and recently even into the physics classes at high schools. As early as 1986, the inventors G. Binnig and H. Rohrer were honored with the Nobel Prize for physics [Binnig, 1987].

The operation principle of the scanning tunneling microscope is extremely simple (figure 5.2.1). It can best be compared with that of an old-fashioned record player, in that it uses a sharp needle to sense the microscopic height variations at the surface of a specimen. The major difference with a record player is that the scanning tunneling microscope’s metal tip does not really touch the surface. Instead, the endpoint of the tip is kept at a short distance of typically 0.7 nm

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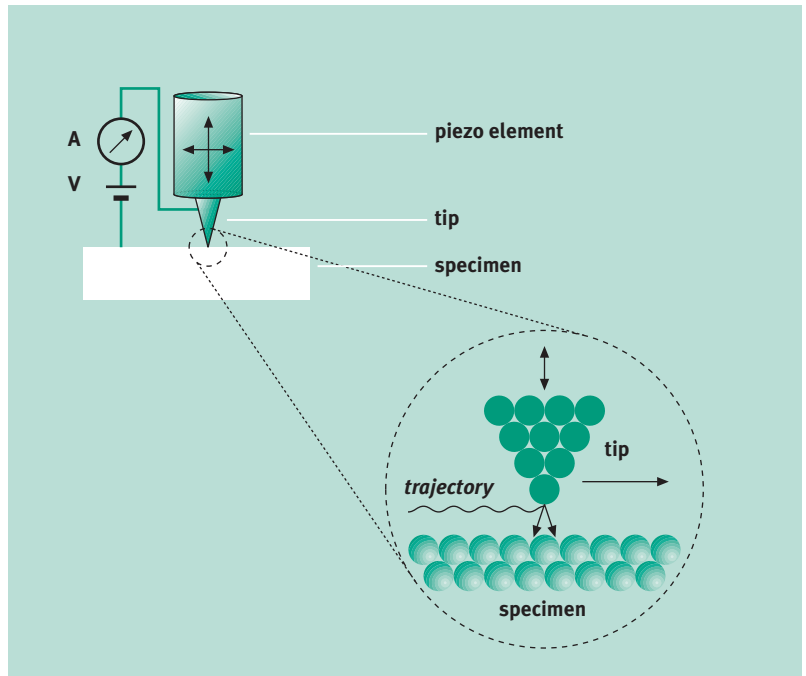
scanning probe microscopy	SPM
scanning tunneling microscopy	STM
scanning tunneling spectroscopy	STS
current imaging tunneling spectroscopy	CITS
tunneling acoustic microscopy	
alternating current scanning tunneling microscopy	AC-STM
reactor scanning tunneling microscopy	reactor-STM
scanning tunneling microscope arrays	micro-STM
atomic force microscopy	AFM
= scanning force microscopy	SFM
contact-mode atomic force microscopy	
friction force microscopy	FFM
scanning friction force microscopy	SFFM
shear-force microscopy	SHFM
force modulation microscopy	FMM
atomic force acoustic microscopy	AFAM
scanning local-acceleration microscopy	SLAM
tapping-mode atomic force microscopy	
non-contact-mode atomic force microscopy	
chemical force microscopy	CFM
electrostatic force microscopy	EFM
Kelvin probe force microscopy	KPFM
magnetic force microscopy	MFM
magnetic resonance force microscopy	MRFM
nanoscilloscope	
scanning Maxwell-stress microscopy	SMM
scanning near-field acoustic microscopy	SNAM
scanning near-field optical microscopy	SNOM
= near-field scanning optical microscopy	= NSOM
photon scanning tunneling microscopy	PSTM
scanning interferometric apertureless microscopy	SIAM
scanning plasmon near-field microscope	SPNM
scanning thermal microscopy	SThM
scanning optical absorption microscopy	SOAM
scanning chemical-potential microscopy	SCPM
scanning capacitance microscopy	SCAM
scanning electrochemical microscopy	SECM
scanning ion conduction microscopy	SICM

Table 5.1.1

Overview of the – still growing – family of scanning probe microscopes (SPMs). Varieties and sub-varieties are indicated by tabs. The term ‘proximal’ is used instead of ‘scanning’, just as the ‘M’ can stand for ‘microscope’ or ‘method’. Information on all these techniques is readily available on the web; see also [Vorburger, 1997] and [Bachmann, 1996].

Figure 5.2.1

Operation principle of the scanning tunneling microscope (STM). A low voltage is applied to the metal tip. Just before the tip touches the surface of the conductive specimen, electrons can 'tunnel' between the endpoint of the tip and the nearby surface. Simple feedback electronics use the resulting tunneling current of typically 1 nA to keep the endpoint of the tip at a fixed distance from the surface. The microscopic position adjustments are made by a piezoelectric ceramic element. When the tip is moved parallel to the surface, the feedback electronics make the tip follow a contour that reflects the atomic-scale corrugation of the surface of the specimen.



(i.e. approximately two atomic diameters) from the surface. This distance is maintained by the following trick. A low voltage is applied to the specimen, of typically 1 V. Just before touching the surface, electrons can already pass from the tip to the surface or vice versa. Hence, the voltage results in a minute electric current, of typically 1 nA (nano-Ampere), even when the tip is at its working distance of 0.7 nm. This so-called tunneling current is very sensitive to the distance. When the distance is decreased by only one atom diameter, the tunneling current increases by as much as a thousand times! By continually measuring the current and adjusting the tip height to keep the current fixed at a constant value of, say, 1 nA, the electronics of the scanning tunneling microscope keep the distance constant between the last atom of the tip and the nearby surface. The sensitivity is so high that the difference between a tip position directly above a surface atom and a position in between two atoms can be detected. When the tip is moved over the surface, while the electronics keep the current constant, the tip follows a corrugated trajectory, which can usually be interpreted as a direct replica of the atomic structure of the surface. The height of the scanning tunneling microscope tip is recorded as it scans the sample line by line to build up a full two-dimensional image of height contours, which is presented as a gray-scale or color image.

If the feedback electronics are set to respond only to slow changes in the current, the trajectory of the tip will only follow the global slope of the surface without exhibiting the corrugation on the atomic scale. The atomic-scale height differences can then be obtained directly from the fast deviations of the current

from its average value. This mode of operation is called ‘constant-height’ mode in contrast to the ‘constant-current’ mode described above.

The tunneling current between the tip and the surface does not depend solely on the voltage and the distance, but also reflects the densities of electronic states of the tip and surface for electron energies close to the Fermi level³. This can complicate the interpretation of measurements when only topographical information on the surface is desired. On the other hand, the scanning tunneling microscope can be used not only to produce straightforward spatial images of ‘where the atoms are’ on a surface, but also to obtain detailed information on the local density of states, and thus the local electronic character of the surface. To this end, one can measure the tunneling current as a function of the tunneling voltage at a fixed distance between tip and surface. If this procedure is carried out at a large number of tip positions, full two-dimensional maps of the local density of electronic states can be made. For further reading on scanning tunneling microscopes, see [Wiesendanger, 1992/1993; Stroscio, 1993; Chen, 1993].

5.2.2 INSTRUMENTAL DIVERSIFICATION

The first scanning tunneling microscopes were complicated ultrahigh-vacuum instruments with high sensitivity to acoustic vibrations, building vibrations and temperature variations of the surroundings. Today’s scanning tunneling microscopes are more compact and have very efficient vibration isolation systems, so that the effects of vibrations and temperature variations are much less severe [Chen, 1993]. Scanning tunneling microscopes operate not only in vacuum, but also in a gas atmosphere (e.g. in air) and in liquids. It is even possible to perform scanning tunneling microscope observations in an electrolytic solution during electrodeposition or erosion, provided that most of the metal tip is covered with an insulating coating.

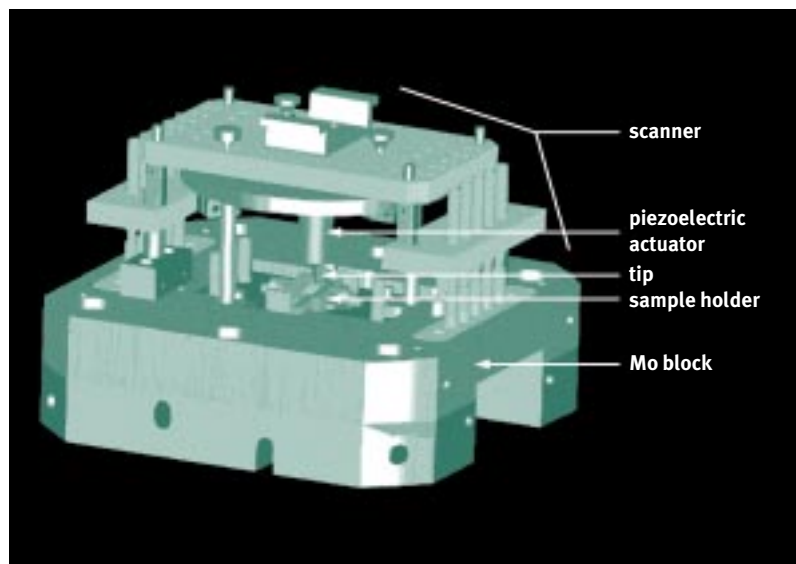
Standard scanning tunneling microscopes for a variety of operating conditions can be purchased from several dozens of companies. The simplest commercial scanning tunneling microscopes are offered for prices as low as approximately \$7,500, and are suitable primarily for educational purposes and for low-level surface analysis. The most sophisticated scanning tunneling microscopes are special-purpose research instruments, often constructed for use in ultrahigh vacuum, and usually offered in combination with a complete vacuum system plus sample and tip storage and exchange facilities. Typical prices for such high-end machines range from \$125,000 to \$500,000. Recent generations of these instruments are no longer developed exclusively at academic research institutions before being commercialized; lately, several commercial companies have been rather successful in developing new types of scanning probe microscopes. Whereas standard scanning tunneling microscopes for use in air have matured to the point that only modest further technical improvement may be expected,

³ The Fermi energy level corresponds to the highest occupied one-electron level at 0 Kelvin.

there is a strong effort to further develop and refine scanning tunneling microscopes for special conditions. In the remainder of this section, several examples of such developments are given.

Figure 5.2.2

Artist's impression of the variable-temperature scanning tunneling microscope developed at the FOM-Institute for Atomic and Molecular Physics. The tip and the piezo-electric ceramic actuator form part of a removable scanner unit. This scanner rests on top of a molybdenum support block, which also carries the sample holder with the specimen. The small sample holder contains a heating element and a temperature sensor. A special configuration ensures that expansions (or contractions) of the sample and the holder do not change the position of the sample surface relative to the tip. As a result, this instrument keeps one region of the surface 'in view' over large temperature intervals of several hundred degrees. The FOM prototype has been successfully commercialized by the British company Oxford Instruments⁴. Reprinted with permission from [Hoogeman, 1998]. Copyright 1998 American Institute of Physics and American Vacuum Society.



A. TEMPERATURE

Much recent work has been aimed at making scanning tunneling microscopes sufficiently insensitive to temperature variations of the specimen to image surfaces in ultrahigh vacuum over a wide range of temperatures. Figure 5.2.2 shows an artist's impression of the variable-temperature scanning tunneling microscope that has been developed in the author's laboratory for temperatures between 50 K and 1000 K [Hoogeman, 1998]. The design was based on computer simulations of the thermal response of the entire microscope, which were used to predict and tailor the full, time-dependent temperature profile of the instrument. As a result, thermal expansions due to temperature changes largely cancel each other and thus do not cause severe displacements or drifting of the specimen with respect to the tip. The stability of specimen and scanner makes it possible to image the same area on the surface over a large temperature range. For example, a particular region on gold crystals can be kept in view during temperature sweeps well over 250 K, in spite of the high thermal expansion coefficient of gold and the high input power needed to heat the relatively large metal specimens.

The variable-temperature capability of our scanning tunneling microscope is exploited in investigations of phase transitions and other temperature-dependent phenomena such as surface diffusion. These phenomena play an important role in processes such as crystal growth, sintering, and catalysis.

Figure 5.2.3 (on page 309) shows two scanning tunneling microscope images of

⁴ Oxford Instruments,
SPM Group
Chesterton Mills
French's Road
Cambridge CB4 3NP
UK

a step, a small region on a gold surface where the height changes by one atomic plane, taken at different temperatures. The image taken at 556 K shows a much rougher step. In fact the step has begun to move, at a rate faster than the scan rate of the scanning tunneling microscope. From the temperature dependence of this phenomenon and a quantitative statistical analysis of the step motion, the complete atomic mechanism of the process has been derived, as well as an understanding how the atomic events combine into mesoscopic-scale mass fluctuations [Kuipers, 1995a]. Scanning tunneling microscope movies of surface diffusion⁵ can be found on the World-Wide-Web.

Other scanning tunneling microscopes are designed especially for low temperatures. Several scanning tunneling microscopes routinely reach temperatures well below 25 K, and some operate at or below liquid He temperature (4.2 K). Low-temperature applications can be found in the fields of superconductivity, atom-by-atom manipulation (section 5.2.3), and the diffusion of individual atoms over surfaces.

B. OTHER ENVIRONMENTS

Originally, surfaces were imaged with scanning tunneling microscopes under conditions where the environment did not react with them. Often this called for ultrahigh vacuum, and only a few materials were sufficiently inert to be imaged with atomic resolution in air. Increasingly, one now uses scanning tunneling microscopes to investigate surface processes rather than mere structures. Examples are diffusion (section 5.2.2A), phase transformations, crystal growth, and surface chemistry.

With the scanning tunneling microscope one can follow the formation of over-layer structures, for instance when a metal surface is exposed to a low dose of a reactive gas [Pai, 1996]. One can also follow the reaction of adsorbed gas atoms or molecules upon exposure to a second gas [Bowker, 1996]. These studies are typically performed at low pressures (below 10^{-5} mbar) and at ambient temperature, in order to keep the adsorption, diffusion, reaction, and desorption rates slow enough for the scanning tunneling microscope to follow the process. These phenomena form the key ingredients of heterogeneous catalysis [Somorjai, 1994]. Industrial catalysis is usually performed at elevated pressures ($P > 10$ bar) and at temperatures of a few hundred centigrade. The enormous pressure gap of a factor 10^{10} between typical laboratory experiments and industrial conditions may be responsible for important unexplored phenomena, such as massive restructuring of the catalyst surface, that contribute to the performance of 'real' catalysts. This calls for new instruments that can image catalyst surfaces in action, which has led to the development of a new microscope nicknamed the 'reactor-STM'. It combines a scanning tunneling microscope with a microreactor in which a controlled flow of a reactive gas mixture can be sustained at pressures up to 5 bar and temperatures up to 300°C, simultaneous

⁵ <http://www.amolf.nl/external/wwwlab/condensed/surfcrys/index.html>

with imaging of the metal surface [Rasmussen, 1998]. The experience acquired with the variable-temperature scanning tunneling microscope was used in the design of this high-pressure, high-temperature scanning tunneling microscope. The reactor-STM produces stable images even under gas flows and during substantial pressure changes. The first experiments on catalyst surface restructuring are currently underway.

C. SCANNING TUNNELING MICROSCOPY ON INSULATORS

Although insulators form an extremely important class of materials, they have not been studied as intensively as metals and semiconductors, simply because many experimental techniques make use of charged particles or electric currents. Obviously, the scanning tunneling microscope does not work on insulators. The electron current immediately charges up the surface under the tip, thereby blocking further current and making it impossible to stabilize the tip-surface distance. One can avoid the charging problem by using very thin oxide films on conductive substrates, but very few oxide materials can be grown in this form [Bertrams, 1995]. A promising alternative is to operate the scanning tunneling microscope under alternating-current rather than direct-current conditions. When an oscillating (AC) voltage is applied of a sufficiently high frequency (e.g., 10 GHz), an appreciable tunneling current on the order of 1 nA can be generated by a single electron that tunnels back and forth between the tip and the surface. The successful operation of an AC-STM on insulators has already been demonstrated [Stranick, 1994]. However, the resolution has not been better than ~ 1 nm, so individual atoms on insulator surfaces have not been resolved with this method. Whether this reflects an intrinsic problem of scanning tunneling microscopy on insulators remains to be seen. Nevertheless, for many applications atomic resolution is not really required and the AC technique is very attractive.

Recently, a new operational mode has been introduced for the atomic force microscope (AFM) that presents an alternative for the AC-STM. In an atomic force microscope, the attractive or repulsive force between the surface and the tip is detected via the deflection of a cantilever to which the tip is attached (section 5.3). In the 'non-contact AFM' the cantilever and tip are made to vibrate at their resonant frequency. At the point of closest approach, the tip is near enough to the surface to experience an interaction. This leads to a modest shift in the resonance frequency and a small phase shift. These shifts can be detected with sufficient resolution to obtain atomic-scale contrast, if (a) the tip performs a 'large' vibration over for instance 10 nm and (b) the instrument is placed in ultrahigh vacuum. The distance of closest approach is comparable to the working distance in the scanning tunneling microscope [Giessibl, 1995]. The first reports of observations on insulator surfaces with atomic resolution are already available [Bammerlin, 1997]!

D. HIGH-SPEED SCANNING TUNNELING MICROSCOPY

Scanning techniques are intrinsically slow, since the information in a two-dimensional image has to be built up pixel by pixel. A typical image consists of 256×256 pixels and requires a recording time of 30 s or more in most scanning tunneling microscopes. The recording time forms a serious obstacle in all present studies of dynamic phenomena on surfaces (sections 5.2.2A and B). It has to be reduced to allow real-time measurements of surface phenomena. For recording of larger images (e.g. 1024×768 pixels) at video rates (50 or 60 frames/s), three technical problems will have to be solved. First, the scanning tunneling microscope construction has to be much stiffer and lighter to prevent it from resonating at the high frequencies involved in fast scanning. Second, the feedback electronics have to be redesigned. Finally, the computer control and data storage have to be sped up to generate, process and store the enormous data flow in such a 'high-definition video STM'. In the given example, the rate of pixel generation is 40 MHz! Clearly, the mechanical aspects require substantial miniaturization of the scanning tunneling microscope scanner unit, while the high data rates require computer power and data storage rates beyond the capabilities of the present systems. However, several partial solutions already exist that lead to a tremendous improvement in speed. High-speed scanning tunneling microscopes have produced movies at 10 Hz [Kuipers, 1995b] and even movies⁶ at 20 Hz [Wintterlin, 1997a; Wintterlin, 1997b] for small images.

In a new method called the atom-tracking scanning tunneling microscope, the tip moves rapidly in a circle with a diameter below 1 nm, rather than scanning entire images [Swartzentruber, 1996]. When this circle is centered around a diffusing atom, the tunneling current is constant. When the atom jumps away from the center of the circle, the current oscillates. Feedback electronics use the current variations to keep the tip's circle centered around the latest position of the atom. In this way, a movie⁷ of the random walk of a single atom or molecule can be recorded with a time resolution that is several orders of magnitude better than with a series of fully scanned images.

E. REPRODUCIBILITY

Although the scanning tunneling microscope can reach atomic resolution, the instrument suffers from substantial irreproducibility and creep in tip position as well as impressive distortion of the images. Accurate and undistorted positioning of the tip, in particular in the two directions within the scanning plane, parallel to the specimen surface, is important not only for properly imaging surfaces. It will also prove necessary for metrological applications (accurate distance measurements) and in other applications of scanning tunneling microscopy that require the tip to be positioned reproducibly over specific locations. Examples

⁶ <http://w3.rz-berlin.mpg.de/~stm/app/fastm.html>

⁷ http://www.sandia.gov/surface_science/stm/a_tracks/a_tracks.htm

are atomic manipulation (section 5.2.3) and the accurate diagnostics, testing and local repair of microscopic devices.

The severe nonlinearities and irreproducibilities in most scanning tunneling microscopes are caused by the piezo-electric ceramic element used to convert the control voltages into the microscopic tip motion. Its response usually depends on temperature, frequency of motion, and even on the voltage history. Much of the nonlinearity can be predicted and corrected for, either during or after the measurements. Nevertheless, this method does not allow accurate, reproducible (re)positioning of the tip on an absolute distance scale.

New methods are being developed to ensure reproducible positioning with an accuracy below 0.1 nm over large distance ranges. These typically involve an independent measurement of the tip displacement. A fully linearized STM has been constructed recently with capacitive distance sensors at the Delft University of Technology [Holman, 1996]. A similar instrument, dedicated to accurate distance measurements is presently under development in the Nanometer-Scale Metrology Group at the National Institute of Standards and Technology (NIST) in the USA. This so-called Molecular Measuring Machine⁸ (M^3) uses an optical interferometry system to measure the tip displacement parallel to the surface. The goal is a 1-nm maximum total uncertainty in point-to-point measurements on a 50 mm x 50 mm range.

5.2.3 MANIPULATION VERSUS IMAGING

Usually, the scanning tunneling microscope tip can be considered to be out of contact with the imaged surface. Still, the presence of a detectable tunneling current implies that there is always some degree of chemical interaction between tip and surface atoms. In addition, tip and surface interact through electrostatic forces and Van der Waals forces (weak forces caused by fluctuations in the charge distributions on the atoms or molecules). These forces are experienced most strongly by individual atoms lying on top of the surface, the so-called ad-atoms. They may respond in several ways to the forces from the tip. If the temperature is high enough for spontaneous diffusion of ad-atoms, the tip may bias this diffusion. This can result in a high concentration of ad-atoms just below the tip. It can lead to the formation and growth of new layers of material and – in dramatic cases – even to the spontaneous rapid bridging of the gap between surface and tip [Kuipers, 1995c]. Once the tip is removed, the newly formed structures disappear as easily as they had appeared. This form of ‘manipulation’ is usually undesirable.

Controlled atom-by-atom manipulation is possible at temperatures low enough to avoid spontaneous diffusion of the surface atoms. Beautiful examples of this can be found in the pioneering work of Eigler and coworkers [Crommie, 1993; Avouris, 1993]. First, the surface is imaged, and one ad-atom is selected for

8

<http://www.mel.nist.gov/div821/webdocs-14/mcubed.htm>

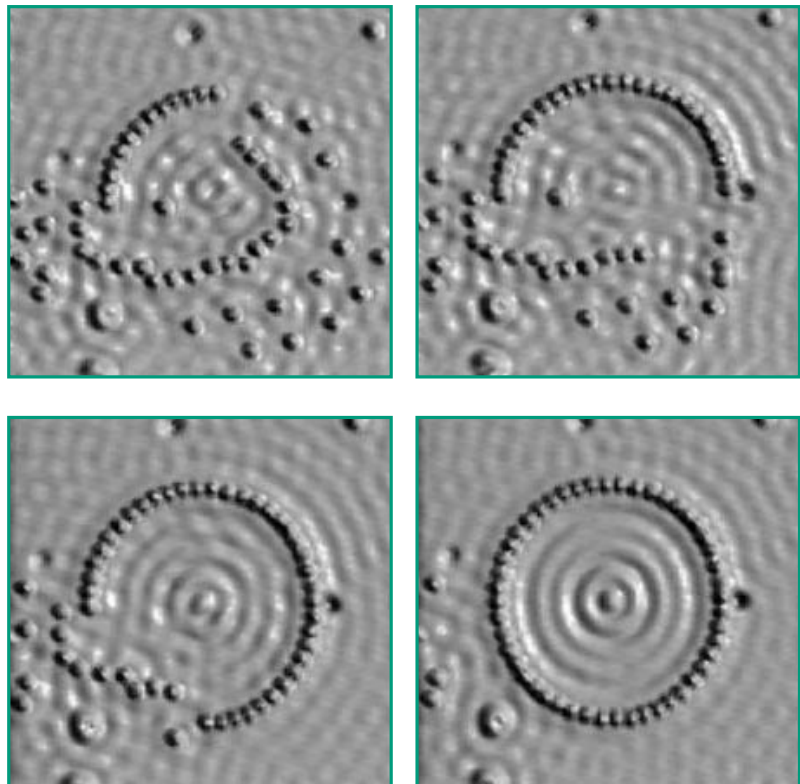
manipulation. The tip is placed directly over the atom and lowered to increase the interaction. Then, the tip is moved parallel to the surface, while the ad-atom has no choice but to follow the tip. Once the atom has arrived at the desired location, the tip is lifted again to decrease the interaction. The tip is then available for further manipulation of other atoms, or for imaging of the new surface structure. The interaction between the ad-atom and the substrate remains sufficiently high throughout the entire process to keep the atom attached to the substrate. The tip forces are very local, so that only one adsorbed atom is moved at a time.

Figure 5.2.4 shows a man-made atomic ring and the interference pattern of electrons ‘confined’ in this structure. At the short length scale of just a few atoms, such quantum effects are the rule rather than the exception.

Not only can one move around single atoms lying on the surface. The removal and replacement of atoms at surface steps of atomic height and even in surface terraces has been demonstrated [Avouris, 1993; Meyer, 1997]. These new manipulation methods open the door towards a kind of ‘atomic-scale construction kit’, which can be exploited to provoke and investigate novel electronic, magnetic, chemical and mechanical behavior in artificial structures. Other possibilities for surface modification, including atomic-scale lithography are treated in detail in section 2.2.4.

Figure 5.2.4

Four stages in the formation of a ‘quantum corral’⁹. A low density of iron atoms were deposited on the surface of a copper crystal, at a temperature of 4.2 K. The individual iron atoms are clearly resolved. The scanning tunneling microscope tip is used to drag 48 iron atoms, one by one, into a ring configuration. The ring forms a barrier (corral) in which some electrons on the copper surface are trapped. Their response as imaged by the scanning tunneling microscope shows quantum mechanics at work. The confined electrons adopt a standing wave pattern with concentric rings and a central maximum (the ‘bump’ in the center of the iron ring is not an atom). See also section 2.2.4. Courtesy of IBM Research Division. Reprinted with permission from [Crommie, 1993]. Copyright 1993 American Association for the Advancement of Science.



⁹ <http://www.almaden.ibm.com/vis/stm/library.html>

5.2.4 CONCLUSION

Almost two decades after its invention, the impact of the scanning tunneling microscope in science and technology is still growing rapidly. Hand in hand with the continued technical development of this type of instrument, of which several examples have been discussed in this section, researchers are discovering new phenomena in the fields of physics, chemistry and biology. Meanwhile, the scanning tunneling microscope is also increasingly being used as a nanotool rather than a nanoprobe, in order to modify surfaces and tailor their structure on the nanoscale, down to the manipulation of single atoms as if they were building blocks in an atomic-scale construction kit, as illustrated by figure 5.2.4. Industrial applications of the latter sort are very remote, but this type of exploratory research does set the stage for possible future devices and the atomic-scale surface properties (electronic, magnetic, mechanical, chemical, etc.) that these devices might exploit. At present, scanning probe microscopes can be found already in industrial settings; these applications form the subject of section 5.5.2.

5.3 ATOMIC FORCE MICROSCOPY

5.3.1 ATOMIC FORCE MICROSCOPE TECHNOLOGY

C.A.J. Putman¹⁰

Introduction

The major drawback of the scanning tunneling microscope is that the sample under investigation needs to be a (semi-)conductor. As a direct result the use of the scanning tunneling microscope is primarily limited to the field of solid-state physics and as such is nowadays widely used as a research tool in that field. In 1986, a new scanning probe microscope was developed [Binnig, 1986], called the atomic force microscope (AFM). This microscope can not only image surfaces of conductors, but also of insulators, both in air, liquid, vacuum and gaseous environments. It therefore allows for the study of interesting samples such as polymers and biological specimens [Marti, 1993]. And in most cases little sample preparation is needed.

The next paragraph begins with a brief description of the basic layout of the atomic force microscope. This is then followed by the various imaging modes of operation, and concluded with a non-imaging mode of operation.

Principle of operation

The operational principle of the atomic force microscope is similar to that of the scanning tunneling microscope. Again, a sharp tip is scanned in close proximity of the surface. However, in an atomic force microscope the tip is mounted on a flexible cantilever (figure 5.3.1 on page 309). For instance, in the first working prototype a sharp diamond shard was glued to a gold foil. Forces acting on the tip will bend the cantilever. By measuring these small vertical cantilever displacements, a map of the sample topography or a map of the forces acting between tip and sample can be obtained. The atomic force microscope can operate on any surface because it measures forces instead of tunneling currents. The four essential parts of the atomic force microscope are the probe (tip + cantilever), the detection system, the scanning stage and the electronics, including the data-acquisition system.

Probes

In the early days, every single probe was hand-made. In 1990, various procedures for atomic force microscope probe fabrication were reported using masking and etching techniques as used in the semiconductor industry [Albrecht, 1990]. This allowed for the fabrication of several hundred probes with integrated tip and cantilever on a single wafer. This not only yielded probes with sharp tips of constant quality, but was also the essential step in the commercialization of the atomic force microscope technique. The first commercial atomic force

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The Netherlands

microscopes from Digital Instruments and Park Scientific Instruments appeared on the market place around 1990. The innovation of new tips has been an ongoing process ever since. Now companies from the USA, Germany, Denmark, Russia and Japan offer a wide range of atomic force microscope probes. Most are made of silicon or silicon nitride and the diameter of the tip lies typically in the 5 to 20 nanometer range. This tip sharpness has a direct influence on the resolution obtained. In general, the sharper the tip, the higher the resolution.

Detection system

There are several ways to detect the small displacements of the cantilever. Optical techniques are the most popular. A robust and sensitive method is the so-called optical beam deflection. Here a laser beam is focused on the backside of the cantilever and the reflected beam is incident on a segmented light detector (photodiode, see figure 5.3.1). If the cantilever moves up or down the reflected beam will shift across the detector. The amount of light incident on the two segments will change and the difference signal between the two segments as well. The changes in this difference signal is thus directly correlated to the movement of the cantilever and tip. Displacements smaller than 0.1 nm can be detected. This is less than the distance between the atoms in graphite (0.25 nm)! Even higher resolutions can be obtained using optical interferometry, but this method proves tedious to operate. There are methods used besides optical detection. In the case of the piezoresistive detection, a material with a resistance depending on the forces (pressure) acting on it is integrated in the cantilever. The integration is a step towards further miniaturization of the atomic force microscope and its probes.

Scanning stage

The sample or tip is scanned by a piezo-electric tube scanner. The electrodes on the tube, which is made of a piezo-electric ceramic material, are dimensioned in such a way that the sample (or tip) can be moved in three dimensions with high precision by changing the voltage. Scan ranges run from several nanometers up to several hundreds of micrometers.

Electronics

Electronics and a data-acquisition system are needed to operate the atomic force microscope and acquire the images. Most data-acquisition systems are PC-based. Most software packages enable the user to analyze the images in detail.

Imaging modes

Contact mode

Over the last ten years, a whole array of imaging modes have been presented. Some of them are widely used, whereas others find only special applications. Three important imaging modes are depicted in figure 5.3.2 (page 310). In contact mode atomic force microscopy, the tip is in repulsive contact with the sample and the tip follows the topographic features on the sample surface. In practice, an electronic feedback loop drives the piezo-electric tube scanner up and down in response to cantilever displacements. In this way it maintains the deflection of the cantilever (and thus the applied repulsive force) at a constant level. By plotting the vertical movement of the tube scanner as a function of xy -position a topographical map of the surface can be obtained.

It takes a little time to reposition the tip in response to the cantilever movements. As a result there are still minute vertical tip movements, that are registered by the detection system. In the *error signal mode* these movements are displayed, which yield high-resolution images.

If a light detector with four segments is used, the torsion motion of the cantilever along its long axis may be monitored while operating in the contact mode. The torsion is induced by lateral forces (parallel to the sample surface) acting between tip and sample. So it is not only possible to detect the edges of topographic features, but more importantly it enables imaging of the friction between tip and sample. Especially on soft surfaces such as polymer films, that show hardly any topographic contrast, it is possible to obtain clear contrast in the *friction force mode*. An artist's impression is shown in figure 5.3.3 on page 310. Furthermore, the various phases present in composite materials or the distribution of lubricants on surfaces can now be imaged with nanometer resolution.

Another method often used is the so-called *force modulation mode*. In this mode, the sample is moved rapidly up and down (typically over a distance of 10 nm at a frequency of 10 kHz) and the response of the tip is detected. If the sample is hard, the tip follows the oscillation, whereas on softer sample features the response of the tip is smaller because the surface gives way to the pressure of the tip. In addition to this amplitude response, also the phase (lagging behind) of the response can be monitored. In this way information on the mechanical strength and elasticity may be obtained. Again, composite materials are interesting samples to study using this mode.

Non-contact mode

In non-contact mode atomic force microscopy, the tip does not touch the sample surface. Instead, long range forces acting on the tip influence the cantilever. A static cantilever will bend. Alternatively, if the cantilever is brought into a

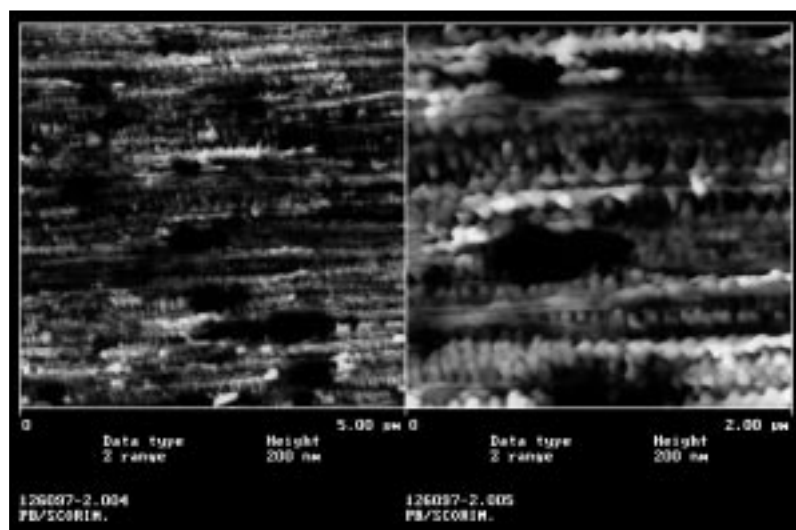
forced oscillation above the surface by the piezosystem, the forces will induce a frequency shift and phase shift in this oscillation (compare section 5.2.2c). The effect of the Van der Waals forces between the surface and tip reveal the topographic nature of the sample surface. Since the tip does not actually touch the surface, this mode is suitable for imaging soft samples, which may otherwise be disrupted by the scanning tip in the contact mode. It is also possible to map magnetic and electrostatic force interactions. Magnetic force microscopes (MFM) are widely used in the recording industry as a research tool [Gutmannsbauer, 1996].

Tapping mode

Since 1994, a hybrid form of contact and non-contact mode atomic force microscopy has been available that combines the best of both worlds. In the *tapping mode* atomic force microscope, the cantilever is forced to oscillate over a vertical distance of several tens of nanometers. The tip briefly and gently touches the sample during each cycle. Since the sample is out of contact most of the time, the destructive influence of the lateral forces is minimized. Moreover, the tapping mode is easier to operate and more robust than the non-contact mode. At the same time, the resolution is almost as good as in contact mode atomic force microscopy. Like all the above-mentioned modes, the tapping mode can be operated in an aqueous environment. This opens up possibilities of studying biological processes such as protein-DNA interactions [Kasas, 1997a]. A recent extension of the tapping mode atomic force microscope is the *phase imaging mode*. By detecting the phase shift of the oscillating cantilever, it is possible to obtain information on tip-sample adhesion and sample stiffness. This mode proves very useful for research on polymer blends and on the morphology of crystalline polymers (figure 5.3.4).

Figure 5.3.4

Atomic force microscope (AFM) image revealing fascinating elements of polymer crystal morphology. The sample was prepared by wet-etching polybutylene, which was oriented using a special technology of Brunel's (SCORIM). The images reveal a 'shish-kebab' crystal structure. Polymer moldings possessing these structures are believed (and have indeed been measured in specific cases) to have higher elastic moduli and better impact properties than conventional materials containing a morphology of spheres. Source: Shell Research (Amsterdam and Louvain-la-Neuve) and Brunel University.

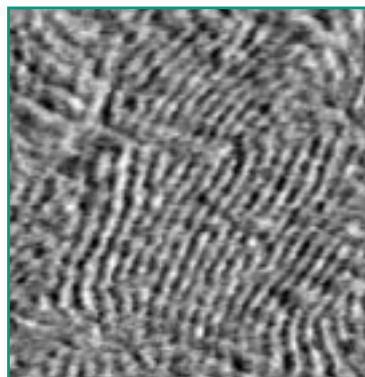
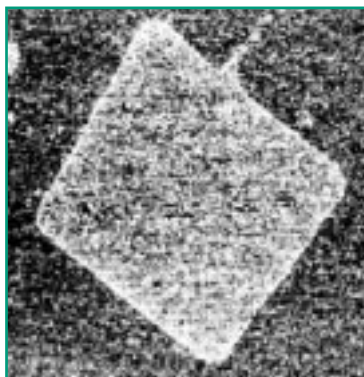


Conclusions

Over the last ten years, the atomic force microscope has become a well-established research tool. It can be operated on a wide variety of samples (with only limited need for sample preparation) and in different environments, such as air, vacuum and liquid. Ongoing innovations in instrumentation and applications has yielded a very versatile apparatus, which will be used by a growing number of scientists in years to come.

Figure 5.3.5 (left)

Chemically specific lateral force image of a gold substrate that has been chemically patterned with $20 \times 20 \mu\text{m}$ squares using microcontact printing (section 2.2.2). Due to the hydrogen bond interaction between the CONH_2 -functionalized tip and the COOH -groups at the surface, the frictional force is higher in the COOH -rich areas (brighter square) than in the surrounding CH_3 -terminated area (darker area). Reprinted with permission from [van der Vegte, 1997]. Copyright 1997 American Chemical Society.



5.3.2 CHEMICALLY SPECIFIC SCANNING FORCE MICROSCOPY

A. ten Wolde

Figure 5.3.6 (right)

Scanning force microscope friction force image ($1.5 \times 1.5 \mu\text{m}^2$) of a film of a star copolymer consisting of blocks of polystyrene (PS) and poly(2-vinylpyridine) (PVP) using a COOH -modified tip. The nanoscale lamellar structure results from phase separation caused by the interaction between the blocks in the copolymers, in which blocks of one type effectively attract their same type and repel unlike blocks. The structure can be imaged using a tip coated with COOH because the friction coefficient of COOH is higher for the PVP part (bright) than for the PS part (dark). Reprinted with permission from [Werts, 1998]. Copyright 1998 Wiley-VCH.

By moving the tip in and out of contact with the sample it is possible to study the nature of the interaction forces. These interaction forces may be fairly non-specific, such as tip-sample interactions on the basis of differences in hydrophobicity. However, by functionalizing the tip it is possible to measure specific molecular interactions, and thus obtain chemical information on the sample. The principle of chemically selective scanning force microscopy – also called chemical force microscopy – is illustrated in figure 5.3.7 of the next section. By coating the tip with biotin (a water-soluble B vitamin) and a sample with the strongly interacting avidin (or vice versa), it has been shown that the adhesion force of the complex can be measured directly via mechanical means [Florin, 1994]. The vertical stretching and relaxation of polymer molecules has also been studied in this way [Rief, 1997]. Although it is possible to operate this force probing in an imaging mode [Berger, 1995], this adhesion mode is not used very often. The discrimination of chirality, a fundamental aspect of chemical biology, has recently been reported [McKendry, 1998].

In an extensive and systematic study, probes and substrates were chemically modified with a variety of functional groups (CH_3 , OH , NH_2 , COOH , and CONH_2) [van der Vegte, 1997]. Chemically specific imaging with a resolution of 100 nm was demonstrated for both uncharged (figure 5.3.5) and for charged surfaces.

The ability to image surface morphologies with a resolution down to 30 nm is demonstrated in figure 5.3.6. Also, the application of an existing theory for adhesion in combination with a recently developed statistical analysis for multiple bonds between tip and surface, allow for the deduction of single-bond forces. Recently, it was demonstrated that nanotube tips can be modified to form nanometre-sized atomic force microscope probes with the capability of chemical discrimination. The modified tips were used to image patterned samples based on molecular interactions and to measure the binding force between single protein–ligand pairs. As the carboxyl groups that are present at the open tip ends are readily derivatized by a variety of reactions, the preparation of a wide range of functionalized nanotube tips should be possible, thus creating molecular probes with potential applications in many areas of chemistry and biology [Wong, 1998].

5.3.3 ATOMIC FORCE MICROSCOPY TO MEASURE SPECIFIC MOLECULAR INTERACTIONS IN CELL BIOLOGY

*C.G. Figdor*¹¹

Introduction

Enormous progress has been made during the past two decades in our understanding of the cell surface and its components. Improved molecular biological techniques have led to the identification of numerous molecules present at the cell surface. These include ion channels (a pore that allows ions to cross the cell membrane), receptors for growth factors (hormones regulating the division of cells), cell adhesion receptors, receptors of the immune system, and the ligands that bind to these various receptors (compare section 4.3). Despite this structural knowledge, there still is no clear picture of the interactions between receptor and ligand at the molecular level. Important questions, like the number of interactions required to induce signaling through receptors, the precise organization of receptor molecules at the cell surface, the forces between receptor–ligand pairs and most of all the dynamics of receptor–ligand interactions have not been answered, or have only been partially answered. Until recently, such studies were hampered by the fact that microscopic techniques that allow for analysis of living cells have a maximal resolution of approximately 300 nm (0.3 micron), depending on the light source used. Although electron microscopy provides much greater resolution (section 3.6 and 4.6), it does not allow study of dynamic systems. Recent developments in scanning probe techniques including atomic force microscopy now facilitate studies of biological systems (cells, organelles and isolated proteins) at high resolution in their natural environment. This is the first method for real-time analysis at nanoscale resolution of biological phenomena such as single receptor–ligand, enzyme–substrate or antigen–antibody interactions.

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In collaboration with the department of Technical Optics of the University of Twente, we have studied the potential of atomic force microscopy to investigate biological systems since 1994. The results, and those emerging from recent literature, demonstrate that atomic force microscopy has come of age and is extremely well suited not only to obtain high resolution topographic maps of biological surfaces, but also to perform actual measurements of single-molecule interactions. Since reliable commercial atomic force microscopes have become available (which allows routine measurements by cell biologists without the need for the constant support of physical engineers), atomic force microscopy will increasingly be applied by cell biologists for in-situ studies to investigate biological systems at the molecular level.

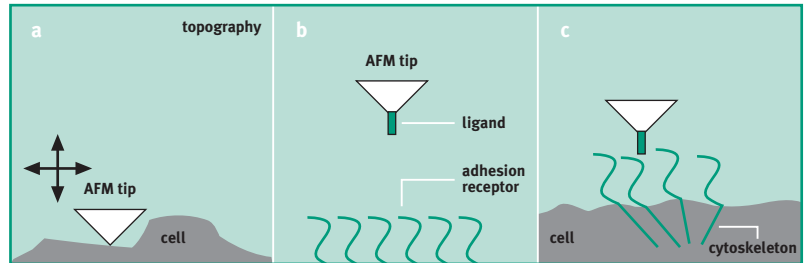
Atomic force microscopy in cell biology

As explained in figure 5.3.1, atomic force microscopy allows analysis of cells as well as purified proteins at the nanoscale level, with a resolution at least a factor 10 to 100 better than other microscopic techniques available for *in situ* investigation. Furthermore, as explained in figure 5.3.7, atomic force microscopy not only results in detailed topographic pictures of cells or proteins, but also permits determination of binding forces between molecules and the dynamic behavior thereof. Also it may provide us with new insights in the coupling of surface receptors with subcellular structures, such as coupling of receptors to cytoskeletal elements (protein-based structures which serve as skeletal elements within the cell) or components of the signaling machinery of the cell. The department of Tumor Immunology at the University Hospital Nijmegen has a long-standing interest in molecules that allow the highly motile cells (cells capable of spontaneous movement) of the immune system to communicate with each other. To this end, the immune cells are equipped with unique receptors highly specific for body foreign substances. How various receptor-ligand pairs interact dynamically at the molecular level is unknown. Nonetheless such information is extremely valuable, not only to increase our knowledge on the receptor-ligand interactions, but also to obtain a better understanding the immune system. Until recently, receptor-ligand interactions could only be studied by biochemical techniques or by surface plasmon resonance, where the receptor or ligand is bound to an artificial substrate or scaffold and the other interacting molecule is in solution [e.g. van der Merwe, 1996]. Neither of these techniques provides detailed insight into the physiology of the interactions. First of all, they are not sensitive enough to study the weak single molecular interactions, and secondly the molecules and receptors that play a role in cell adhesion and communication are anchored into the cell membrane, not free in solution. Now for the first time atomic force microscopy provides a means to study (1) surface-bound interacting molecules (2) at high resolution at the single molecule level (3) in their natural environment. Recent reviews [Allen, 1997;

Kasas, 1997b] illustrate the power of this technique for the comparison of avidin-biotin interactions with antigen-antibody interactions. Biochemical studies reveal that avidin-biotin are amongst the highest affinity interactions in nature. The first atomic force microscope measurements showed that the force required to break one biotin-avidin interaction was 160 piconewton (pN) [Florin, 1994].

Figure 5.3.7

a A topographic picture can be made of, for example, a cell.
b When the tip is modified, for instance by coating with a ligand, receptor binding and unbinding forces and the dynamics thereof can be measured by moving the tip up and down.
c When a ligand-coated tip binds to a receptor present on the surface of a cell, this allows measurement of the receptor-ligand interaction forces. Also, movements along the surface allow measurement of the receptor interacting with molecules inside the cell (i.e., underneath the cell membrane), such as cytoskeletal elements. The outcome of treatment of the cell with stimuli or drugs can be investigated as well.



Surprisingly, the group who published the first antibody-antigen interaction ever measured by atomic force microscopy showed that this interaction was even stronger (240 pN) than that holding avidin and biotin together [Hinterdorfer, 1996]. This clearly illustrates that totally different rules must be applied when surface-bound rather than free-floating molecular interactions are studied. Immunologists and cell biologists studying cellular interactions are particularly interested in surface-bound molecules. Atomic force microscopy will fill in this gap and allow the study of single molecular interactions. World-wide, atomic force microscopy is primarily used to investigate materials in air. However, since biologists want to study biological systems in their natural environment, a significant amount of time has been spent during the past few years to optimize the equipment for measurements in solution (a cell culture medium or physiological salt solution). Also techniques have been developed to immobilize isolated proteins to a surface by photo-induced chemical crosslinks (photolinking) and to use spacers to increase the probability that ligands and receptors interact with each other.

Future prospects

Thus far, most studies concern interactions of antibody- or ligand-modified tips with isolated proteins absorbed or covalently linked to mica surfaces. But the dream of a cell biologist is to study these biomolecules in their natural environment: a living cell. Before this dream can become reality, a large number of hurdles must still be overcome. Examples are the flexibility of the cell membrane, the instability of the atomic force microscope equipment, and the difficulty of discriminating non-specific from specific interactions. Despite these present obstacles it is to be expected that scanning probe techniques will become an invaluable tool to study cells at the molecular level, and will eventually belong to the standard equipment of a cell biology laboratory.

5.4 NANOMETER-RESOLUTION OPTICAL MICROSCOPY

5.4.1 FAR-FIELD OPTICAL METHODS

B.G. de Grooth¹², Inge M. Peters, M.L. Bennink, J. Greve

Since the invention of the optical microscope by Antony van Leeuwenhoek, conventional optical microscopy has reached a high level of sophistication and established itself as the most widely applied microscopic tool through its flexibility, applicability and multitude of optical contrast methods. The equipment is relatively simple and cheap, specific staining techniques have been developed that allow the identification of subcellular structures, as well as immunological labeling methods to identify and locate specific proteins. A technique for optical labeling of biological systems (in-situ hybridization, section 5.4.2) has also provided an new impetus.

However, the spatial resolution for far-field optical microscopy (measuring and exciting in the far field) is fundamentally limited by the wavelength of visible light (380 to 780 nm). With a lens, it is impossible to focus light to a spot with dimensions that are smaller than half the wavelength. A second limitation of conventional microscopes is that the quality of the image is seriously degraded by the blurring action of the material out of focus. This has been greatly improved by the development of the confocal fluorescence microscope [Wilson, 1990].

One obvious way to achieve nanoscale resolution is to decrease the wavelength leading to x-ray (0.001 to 10 nm) and electron microscopes (section 3.6).

Although these instruments are of great use, they are unable to work with living samples. Today, there are two approaches aimed at the improvement of the spatial resolution of optical microscopes. The first way, described in this section, optimizes the use of far-field optics. The second approach is to measure or to excite in the so-called near-field region of the optical field (section 5.4.2).

4 π microscopy

For a practical situation of visible light at a wavelength of 500 nm and a molecule embedded in water (the wavelength depends on the medium through the refractive index) the best *possible* resolution would be 60 nm. Thus, the fundamental resolution of an optical measurement is much better than currently achieved with optical microscopes and can be expected to improve to about 50 nm in the coming decade. The above-mentioned optical resolution limit of half of the wavelength of the light can be improved significantly by illuminating the sample from different sides, for instance by placing the sample between two objectives with a high numerical aperture (section 2.2.1), provided that the light coming from both directions is coherent. In addition, a similar improvement in resolution can be achieved by using these objectives to collect the light, provided that it is combined onto a single detector. The method is called 4 π micro-

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Figure 5.2.3

Two images of a small piece of the surface of a gold crystal cut along the (110) plane. The parallel stripes are close-packed rows of gold atoms. The distance between these rows is 0.8 nm. The imaged region contains a step between two planes of gold atoms with a height difference of 0.14 nm. At the lower temperature (upper image) the step is static, and individual 'kinks' can be seen in the step. At the higher temperature (lower image), the frequent arrivals and departures of individual diffusing gold atoms at the step result in such a rapid fluctuation of the shape and position of the step, that the scanning tunneling microscope is too slow to image the step properly. Between subsequent scan lines in the image, the step has moved over several lattice spacings. Reprinted with permission from [Kuipers, 1995a]. Copyright 1995 by the American Physical Society. See page 293 and further.

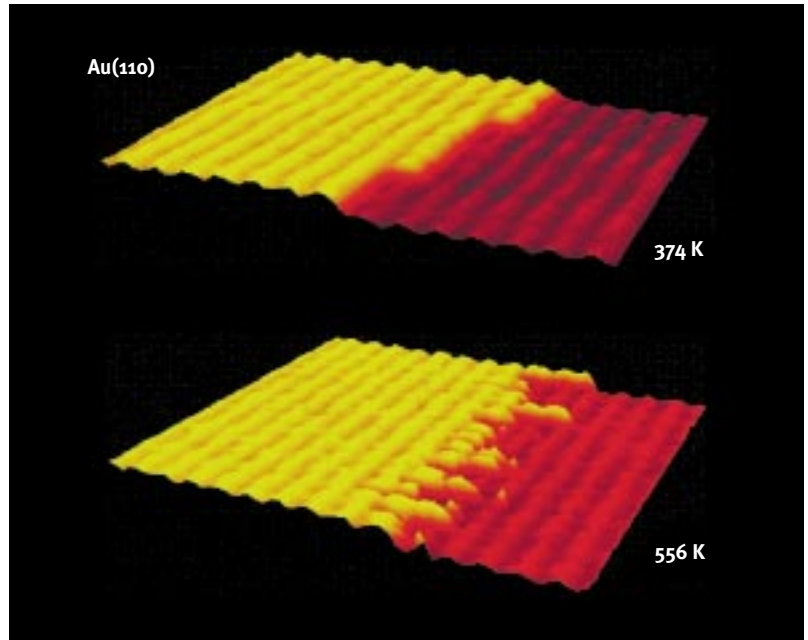
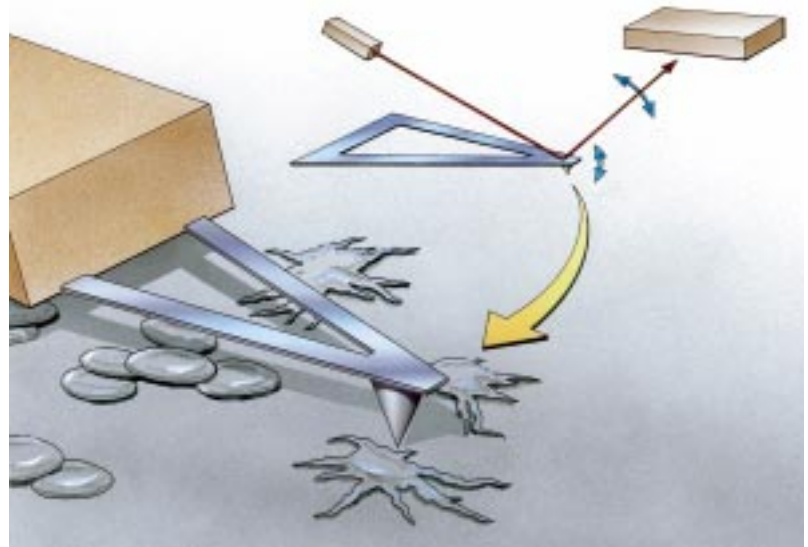


Figure 5.3.1

The basic principle of operation of an atomic force microscope (AFM). A tiny (10 nm diameter) tip is mounted on a cantilever that is illuminated by a laser beam. The reflected light illuminates a detector. If the tip touches a surface the cantilever bends, resulting in a difference in reflection of the beam onto the detector. Piezoelectric elements drive the cantilever such that the tip follows a surface – or a structure on a surface, such as a cell – with nanometer precision. See page 300 and further.



scopy because illumination of the sample and collection of the light take place from almost all directions (over a solid angle of almost 4π) [Hell, 1992].

Nanovid microscopy

Despite the limits of resolution in an optical microscope, if – and only if – it is known that the light detected is due to a single particle, its position can be determined with arbitrary accuracy, only limited by the amount of light collected during the measurement. In practice, the position of small particles can be

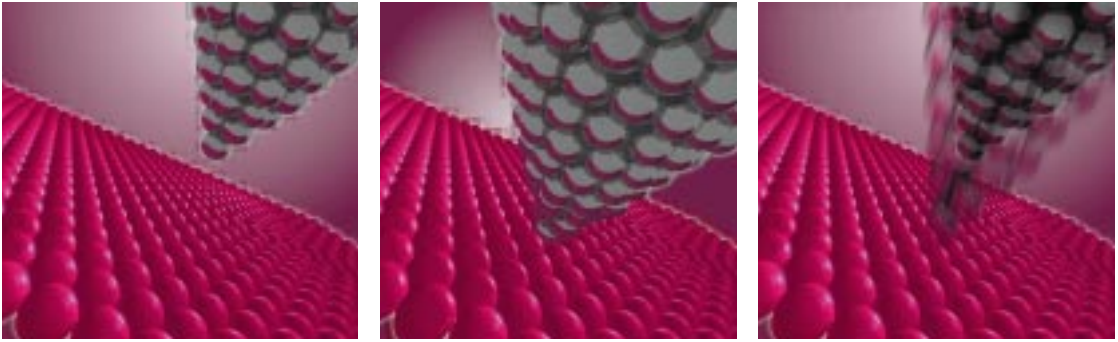


Figure 5.3.2
 Three imaging modes of atomic force microscopy: contact (left), non-contact (middle) and tapping mode (right). See page 302.

Figure 5.3.3
 Artist's impression of an atomic force microscope tip probing a soft surface. See page 302.



Figure 2.5.2
 The measured current through the quantum dot from figure 2.5.1 as a function of the gate voltage and the bias voltage. When the voltage is increased above certain thresholds, an extra electron enters the quantum dot. The size of the blue diamonds determines the amount of energy that is necessary to add this electron, which is the equivalent of the ionization energy for this artificial 'pancake' atom. Reprinted with permission from [Kouwenhoven, 1997]. Copyright 1997 American Association for the Advancement of Science. See text on page 122 and further.

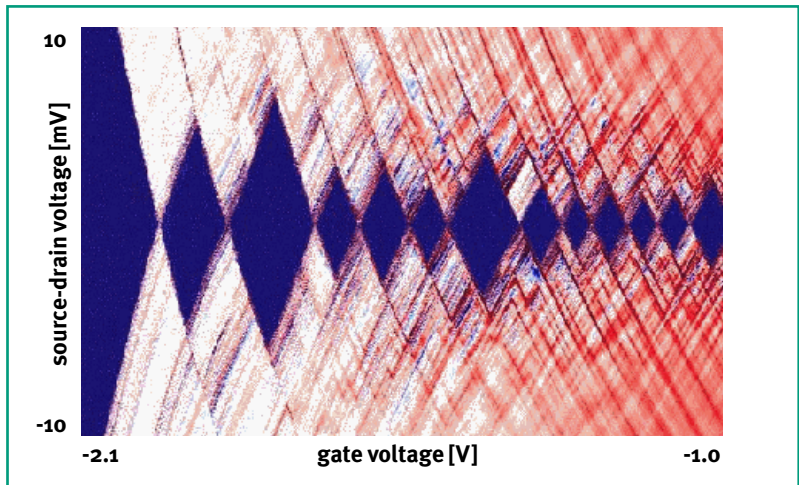
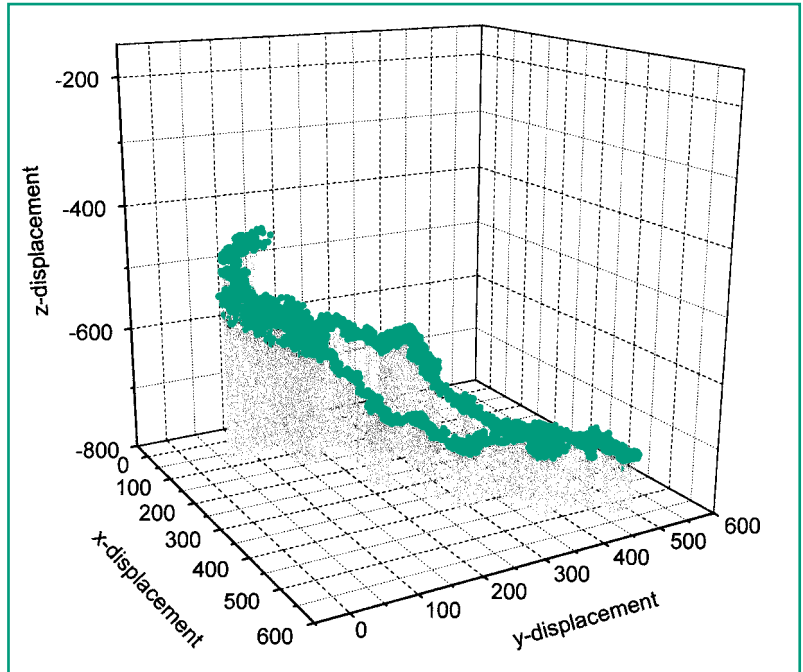


Figure 5.4.1

Three-dimensional motion of LFA-1 adhesive marker molecules on mouse cells measured with the single particle tracking technique [Peters, 1998].



determined with a precision of *less than 1 nm*, limited by mechanical instabilities rather than by the optical method.

This principle has been applied to gold particles with sizes of about 30 nm [Geerts, 1987]. A conventional microscope was equipped with a television camera. The nanoparticles become visible by averaging the signal. Increasing the averaging time at high magnification allows to determine their position with a resolution of 5 nm at video rate. This technique is often referred to as nanovideo microscopy. Labeling of cellular structures with the gold nanoparticles, that were in turn labeled with monoclonal antibodies, has allowed for the study of, for instance, diffusion of proteins in the cell membrane with a resolution of about 2 nm.

A variation of this technique is to use laser light that is focused on a small particle. By analyzing the scattered light with position-sensitive detectors, the position of the particle can be determined in three dimensions with a resolution of 1 nm as illustrated in figure 5.4.1 [Peters, 1998].

Optical tweezers

Light can also be used to manipulate particles. The basic principle is very simple. Light carries momentum. When reflected by a particle with a different refractive index than the surrounding medium, the light changes direction. Since momentum is conserved, the particle has to move the other way. As a result, reflecting light pushes a particle forward in the direction of the light beam. Similarly, light that is refracted inside a particle pulls it to the brightest

area. Hence for a strongly focused laser beam, somewhere closely behind the focus exists a stable position in three dimensions. In this way a particle can be trapped. By moving the laser focus, the particle can be moved to a specified position. Using the particle-tracking method discussed before, it is possible to manipulate the particles with an accuracy of about 1 nm in three dimensions. The method is often referred to as optical tweezers. Optical tweezers have been used extensively for manipulating microsized particles and biological structures [Svoboda, 1994]. In addition, optical tweezers can also be used to determine external forces on a trapped particle. An observed displacement of the particle with respect to the laser beam directly corresponds to a force on the particle. As an example to illustrate the use of optical tweezers in the field of nanotechnology, we describe a recent experiment used for studying the mechanical and structural aspects of individual DNA molecules [Smith, 1996; Bennink, 1998]. As depicted in figure 5.4.2, both ends of an individual DNA molecule can be attached to different polystyrene beads. Using the optical tweezers in combination with a micropipette, the DNA molecule can be stretched. During this stretching process the relation between the extension of the DNA molecule and the force acting on the molecule can be obtained. A typical example is shown in figure 5.4.3.

Figure 5.4.2

Stretching an individual DNA molecule: the ends of the molecule were attached to two different polystyrene beads and pulled apart using the optical tweezers in combination with a micropipette. Reprinted with permission from [Bennink, 1998]. Copyright 1998 Nederlands Tijdschrift voor Natuurkunde.

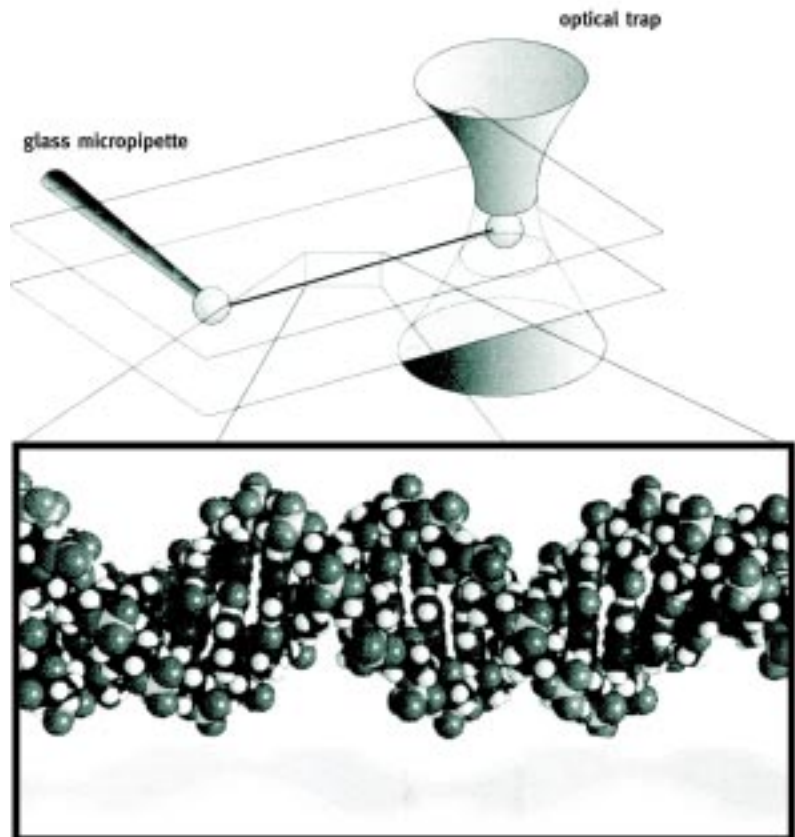
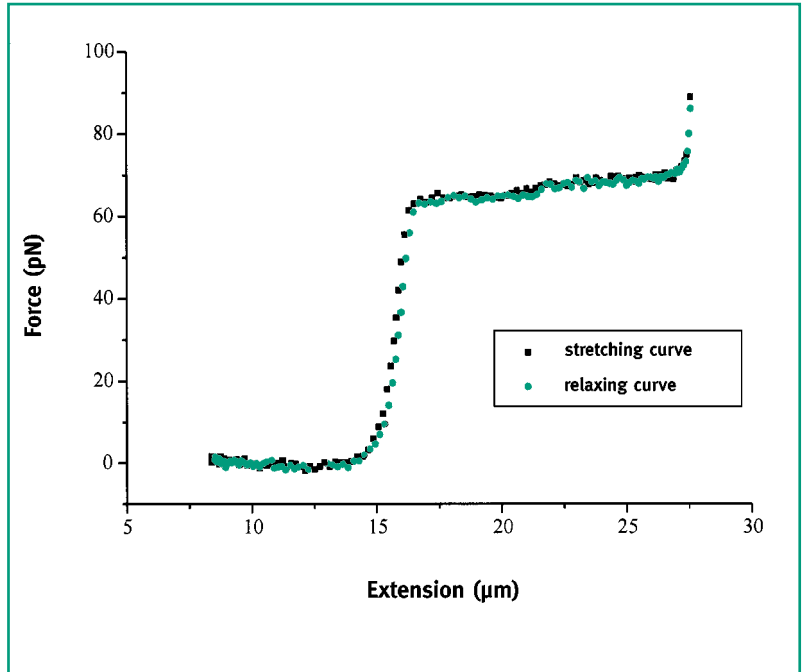


Figure 5.4.3

Force versus extension of a single DNA molecule of 17- μm length that was stretched with 2- μm beads using the setup in figure 5.4.2. For small extensions (up to about 16 μm) the DNA bonds are simply stretched. For applied forces above 65 pN (10^{-12} N) the flat curve indicates a structural transition of the molecule to an overstretched state which is roughly 1.7 times the length of the unperturbed double helix, and undertwisted [Bennink, 1998].



5.4.2 SCANNING NEAR-FIELD OPTICAL MICROSCOPY

N.F. van Hulst¹³

Scanning near-field optical microscopy (NSOM or SNOM) is a combination of scanning probe microscopy and optical microscopy. Over the last decade it has become possible for users of classical optics to go beyond the diffraction limit using so-called near-field optics. The strength lies in the potential to combine the best of both worlds. The increasing significance of nanometer-sized structures in electronics, material science, chemistry and biology has made the study of the near-field optical properties of nanostructures highly appropriate and stimulated the development of both instrumentation and theory.

TYPES OF SCANNING NEAR-FIELD OPTICAL MICROSCOPES

Aperture type

Far-field optical microscopy is based on the imaging of light waves traveling from the substrate through a far-away lens to a detector. However, light coming from a spot on the substrate with sub-wavelength dimensions cannot form a traveling wave. As a consequence, far-away lenses cannot be applied to image nanostructures illuminated with a beam of light. Instead near-field optics is based on some kind of nanometer-sized probe or source that interacts on a sub-wavelength scale with the local sample to be examined. In figure 5.4.4, the

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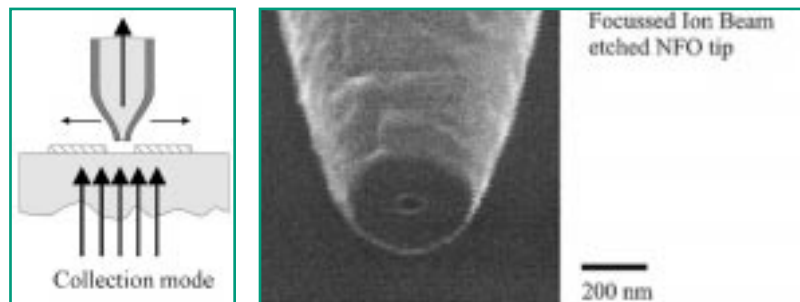
principle of operation for near-field microscopy is explained for the example of an aperture-scanning near-field scanning optical microscope used in the collection mode. In this case the probe is formed by a tapered glass fiber with a nanometer-sized aperture. It collects the light from the underlying nanosize spot on the surface and directs it to a conventional optical detector. The image is constructed by scanning the probe over the surface. The spatial resolution of typically 20 to 100 nm is determined by the size of the probe and is basically independent of the applied wavelength. It may come as a surprise that the light waves – having wavelengths of hundreds of nanometers – can pass through the nanometer-sized tip at all. However, the situation is not much different from the following, more familiar situation. When you listen, you detect sound waves with a wavelength of several meters. Still, these waves have no trouble finding their way through your centimeter-scale ears!

Figure 5.4.4

The aperture-type near-field scanning optical microscope (NSOM or SNOM) used in the collection mode. The sample is illuminated over a large area, from beneath. The transmitted light is collected by a glass fiber probe with a nanosize aperture that is scanned over the surface at a distance of a few nanometers. The local sample structure influences the light entering the aperture. This change is transmitted by the light traveling through the fiber and measured by the detector.

Figure 5.4.5

Near-field optical probe with an aperture diameter below 100 nm surrounded by aluminum. It was fabricated by successive (1) adiabatic (slow) tapering of an optical fiber using a special purpose fiber puller, (2) aluminum evaporation and (3) focused ion beam etching. The approximately 100-nm-thick aluminum coating screens out the far-field light. Source: J.A. Veerman, MESA Research Institute, Twente University, Enschede, The Netherlands.



The aperture type is the most widely used configuration. The first near-field optical microscope had a resolution of 20 nm using an aperture at the apex of a sharpened quartz rod. Today, fiber probes are fabricated in efficient and reproducible ways. Figure 5.4.5 shows a typical aperture probe. Of course most of the incoming light is lost. This probe transmits about 10 nanowatts (nW) of light when several milliwatts of laser light is coupled into the fiber. More laser light would burn the aluminum coating.

The probe is the heart of any near-field optical microscope. The probe interacts with the sample and transmits the modulated response to the detector. It therefore determines the contrast mechanism, the spatial resolution and the sensitivity. As such the importance of the probe is comparable to that of the objective lens in far-field optical microscopy. Ideally, the probe is of molecular dimensions. However, it has to be manipulated in a scan pattern over the surface and addressed to collect the near-field interaction information. This is why the probe is always a macroscopic tip ending in a nanometer-sized apex supporting the source or detector. Fabrication of an optical source or detector of nanometer size dimensions is a challenge in itself. Many types of probes have been fabricated. For instance, various experimental designs using luminescent particles or sub-micron-sized light detectors were tried but never fully developed.

The probes are used in various configurations. For instance, the aperture-type near-field scanning optical microscope can also be used in the transmission mode (figure 5.4.6). In this case the probe serves as a source instead of a detector. High-resolution imaging can only be expected while operating the probe at a distance of only a few nanometers from the surface. At this distance – a fraction of the wavelength of the light – the light is confined to the dimension of the

Figure 5.4.6

The aperture-type near-field scanning optical microscope (NSOM) in the transmission mode. The incoming light is transported close to the surface through a glass fiber with a nanosize aperture illuminating a nanosized area of the sample. The light coming out of the aperture is modulated by optical interaction with the sample and detected below the substrate.

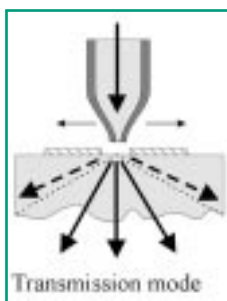
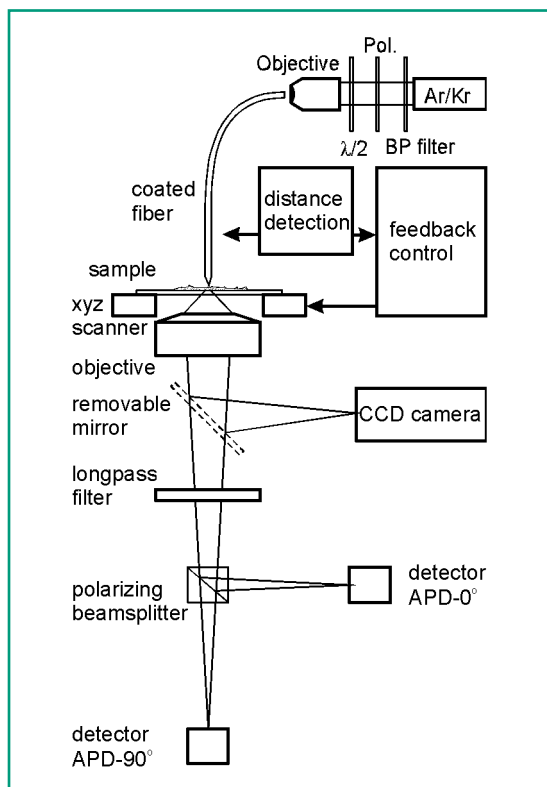


Figure 5.4.7

Experimental setup of an aperture-type near-field scanning optical microscope (NSOM) with a metal-coated tapered fiber in the collection mode. The scanning sample stage is mounted on top of an inverted optical microscope. The distance between tip and sample is controlled using a shear-force sensor mounted to the fiber (see further). The transmitted light is collected over a large angle by a special objective. The resulting beam is led through a filter transmitting fluorescent light from the surface only. The fluorescence is divided over two detectors to obtain information on the polarization.



aperture. At larger distances the spot size rapidly expands. For many applications it is important that the sample can be viewed with conventional high magnification optics for localization of a specific area of interest. This can be realized using an inverted conventional microscope configuration with sufficient mechanical stability on the nanometer scale (figure 5.4.7). The inverted configuration leaves sufficient space for the mounting of a near-field optical probe in the immediate vicinity of the sample surface.

The next paragraphs describe two other configurations encountered in practical near-field optical microscopy, namely the antenna (or ‘apertureless’) type and the photon-tunneling configuration.

Antenna or 'apertureless' type

The antenna-type probe is simply a passive nanometer-sized metallic tip. The tip is illuminated with a tightly focused laser beam with a submicron spot size. The local interaction with the sample surface is subsequently detected as a modulation in the scattered light (figure 5.4.8). Extreme sensitivity is required to observe this modulation in the presence of the light scattered from the sample [Zenhausen, 1995]. Images with a resolution of a few nanometers were obtained in this way. However, this configuration is far from routine. It can only be operated on rather specific samples and requires strong illumination.

Figure 5.4.8

The antenna type: the scanning probe consists of a nanosized metal tip. The surface is illuminated over a large area from above or beneath the sample. The local interaction of the metal tip with the sample surface is detected as a modulation in the scattered light.

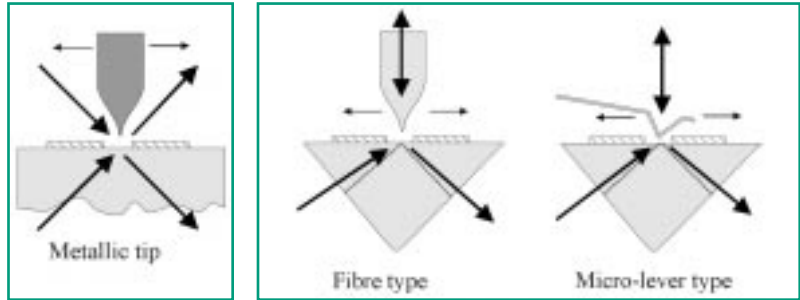


Figure 5.4.9

The photon scanning tunneling microscope (PSTM): the sample is placed on a supporting glass substrate. By illumination at an angle sufficiently parallel to the surface, an optical field is created that propagates along the sample over a large area. A fraction of this wave is coupled by 'optical tunneling' into the probe (a fiber or a micro-fabricated lever) and detected.

Photon scanning tunneling microscopy

An alternative arrangement is photon scanning tunneling microscopy (PSTM, figure 5.4.9). The operation with uncoated probes makes photon scanning tunneling microscopy experimentally easier than the aperture type. Occasionally, a lateral resolution down to 20 nm is obtained [Moers, 1994a]. However, this microscope is very sensitive to far-field scattering. This limits the method to very flat samples and severely limits the application to, for instance, biological samples.

Solid immersion lens (SIL)

Optical microscopy with a solid immersion lens (SIL) is a way to push the diffraction limit for imaging by working in near-field operation in the vertical direction. In contrast to other ('real') near-field methods, it works in far-field operation for the lateral directions, just like confocal microscopy. However, the solid-immersion-lens method is of considerable industrial importance because it allows for high-density recording (section 1.2). It pushes the current technology for optical recording by reducing the distance between the focusing lens and the storage medium below the wavelength of the light. Under these circumstances, the evanescent field overlap allows the lens to act like a magnifying glass lying on a newspaper. The addition of a solid immersion lens will reduce the spot size by a factor of n^2 , with n the refractive index of the lens. One factor of n arises from the wavelength reduction inside the lens and one factor from the increase in the maximum angle of incidence due to refraction at the lens surface [Mamin, 1995].

Using a glass lens with a refractive index of 1.9, this allows for a reduction of the spot diameter by a factor of 3.5, to about 125 nm. This means an increase in storage density by a factor of 10 compared to commercially available optical data storage media and tough competition for the current magnetic hard disks. The advantages of near-field data storage using a solid immersion lens are non-contact, high-density, high-speed (up to at least several MHz) operation. The main limitation is that the spot size is still diffraction-limited due to the far-field operation in the lateral direction, and cannot be reduced any further. Using near-field operation in all three directions could push the spot size beyond the diffraction limit down to 20 to 80 nm, which would add an extra factor of 10 to the optical data density, though with loss of light and an ultrashort working distance as complicating factors. Densities as high as 170 Gb/in² (60-nm bits) have already been reported [Hosaka, 1997].

Shear force microscopy

The use of a fiber probe in close proximity to the sample surface requires a highly sensitive distance sensing and regulating mechanism to keep the fiber from crashing into the surface. Fortunately, with the development of scanning tunneling and atomic force microscopy, this problem has been solved through the use of piezo-electric manipulators responding to the measured probe-sample interaction (sections 5.2 and 5.3). Force microscopy with tapered fibers was first demonstrated in 1992 [e.g., Toledo-Crow, 1992]. The fiber probe is attached to a piezo-electric element. This element brings the fiber into a rapid forced oscillation parallel to the surface over a distance of about 25 nm, thereby only slightly decreasing the lateral resolution. The oscillation amplitude decreases on approaching the sample surface due to 'shear' forces between probe and sample. This change is detected by the electronic actuators of the piezo-element and converted into distance information. Using an electronic feedback system based on this shear force detection, the distance between probe and surface can be adjusted between 1 and 15 nm with a vertical sensitivity of about 0.1 nm. Simultaneously a topographic 'shear' force image of the surface, similar to regular atomic force microscopy operation, is obtained 'for free'.

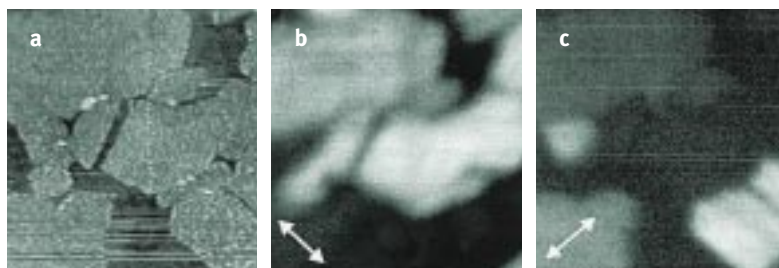
APPLICATIONS

The feasibility of near-field optics has been explored experimentally since 1982 [Pohl, 1984] only one year after the demonstration of scanning tunneling microscope in 1981, and four years before atomic force microscopy. Though among the first in the expanding variety of scanning probe methods, near-field optics has been struggling with probe fabrication for almost a decade, while tunneling and especially force microscopy have developed into widely used surface analysis tools with nanometer resolution. Yet, despite the outstanding vertical and lateral sensitivity of scanning tunneling and atomic force microscopy, optical

microscopy has remained essential. It is convenient, non-invasive, non-destructive, it can operate in a native environment (in vivo). It also has a high contrast, is fast and in particular highly chemically specific due to the obtained spectroscopic information. In comparison, the chemical specificity of force sensing is only beginning to emerge [Dammer, 1995]. The first applications of near-field optical microscopy to biological and chemical samples used the relatively efficient aperture probes [Moers, 1994b]. Near-field optics has only recently started to show its latent promises of optical contrast at nanometer dimensions with improving efficiency and versatility [Paesler, 1996]. The steadily growing number of applications in material science, optoelectronics, chemistry and biology is indicative of its future importance in nanotechnology [van Hulst, 1996].

Figure 5.4.10

A $4 \times 4 \mu\text{m}^2$ scan of a Langmuir-Blodgett monolayer of polymers on a glass substrate. (a) Shear force image with a lateral resolution of about 30 nm, showing the topography of several uniform 8-nm thick polymer monolayer domains, including some surface roughness and a few non-fluorescent structures; (b, c) simultaneously recorded near-field fluorescence images with about 100-nm lateral resolution for excitation with mutually perpendicular directions of linearly polarized light (indicated by the arrows). The domains that emit fluorescent light in one image are dark in the other. This clearly shows the high anisotropy of the film and indicates the orientation of the polymer chain, which is uniform over each domain due to the crystallinity of the film. Reprinted with permission from [Moers, 1994b]. Copyright 1994 American Chemical Society.



Monolayers

A Langmuir-Blodgett film is a highly organized and oriented one-molecule-thick layer. Generally these films serve as model systems for molecular organization in (bio)chemical membranes. For near-field optical microscopy, Langmuir-Blodgett films are ideal objects of study, because of their homogeneous, ultra-flat surface and their well-defined molecular orientation. An example clearly demonstrating the advantage of near-field optics in combination with force microscopy is given in figure 5.4.10.

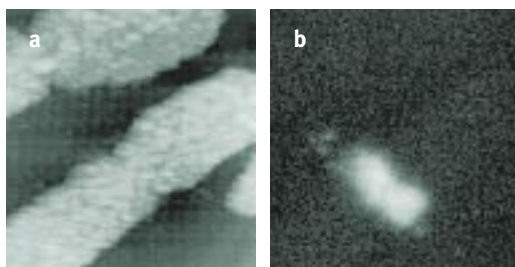
Chromosomes

Human chromosome structure has been investigated with all microscopic techniques available. Chromosomes can be chemically labeled with small molecules with a technique called in-situ hybridization. By using label molecules that emit fluorescent light upon illumination with, for instance, a laser, the labels can be detected using a microscope. Fluorescence in-situ hybridization (FISH) has become one of the major methods for the analysis of human cellular genetic material. It enables direct visualization of topological or positional information of gene sequences in a conventional fluorescence microscope, allowing rapid localization of DNA fragments in morphologically preserved chromosomes. By using labels emitting light with different colors, multiple processes can be examined simultaneously through multicolor fluorescence detection. However, in conventional fluorescence microscopy, the position of the fluorescence labels

can only be determined with a resolution of about $0.3\ \mu\text{m}$ due to the fundamental diffraction limit. Localization of the numerous closely linked genes requires mapping at higher resolution. This can be achieved using electron or force microscopy. Using electron microscopy, some DNA samples can be imaged with nanometer resolution. Atomic force microscopy can discriminate morphological labels of 75 to 100 nm diameter [Putman, 1993]. However, these methods lack the multiplicity of fluorescence detection. Near-field fluorescence microscopy has the potential to combine the best of both: optical resolution beyond the diffraction limit and multiplicity with sensitivity down to the single molecular level. Figure 5.4.11 shows a fluorescence near-field optical microscopy scan combined with simultaneous shear force detection of human chromosomes.

Figure 5.4.11

A $7 \times 7\ \mu\text{m}^2$ scan of a human chromosome. The chromosome was labeled with fluorescent molecules by in-situ hybridization (FISH). (a) Shear force image showing the chromosome topography with some substructure; (b) corresponding near-field image of the green fluorescence light emitted upon laser illumination, displaying about ten labeling molecules in the central area of the chromosome. Reprinted with permission from [Moers, 1996]. Copyright 1998 Royal Microscopical Society, Oxford, UK.



Single fluorescent molecules

The observation of individual molecules is an application of near-field optical microscopy as a scientific tool. By tracking the exact position and orientation of a molecule, many dynamic biological processes can be studied, such as protein and molecular conformational changes. Moreover, the single molecular response provides a sensitive tool to study the local environment of a single molecule at biologically relevant conditions. For instance, the accuracy of a measurement of the fluorescence energy transfer between a donor and acceptor pair depends critically on their relative distance and molecular dipole orientation. In addition, selective excitation of molecules with a particular orientation can be exploited as a tool to trigger or inhibit specific biological reactions. To date, light microscopy of single molecules at ambient conditions with high spatial and temporal resolution is readily achievable by ultrasensitive fluorescence detection [Xie, 1996]. Also, single molecules can be imaged using the near-field method. They have been localized within a few nanometers and their orientation in three dimensions could be determined [Betzig, 1993]. This achievement was directly followed by single molecular spectroscopy [Trautman, 1994] and single molecular fluorescence lifetime detection [Xie, 1994]. A typical example of the dynamics of single molecules as observed in near-field fluorescence is shown in figure 5.4.12 on page 327. A sample consisting of carbocyanine fluorescent molecules embedded in a thin PMMA (polymethyl methacrylate) layer was prepared by spin-coating (section 3.7). This resulted in

a 5 to 10 nm layer with a surface coverage of typically a few dye molecules per square micrometer. Figure 5.4.12 (on page 327) shows a series of 'snap shot' images displaying single carbocyanine molecules. Note that molecule 7 remains fixed during one hour in images (c) to (h), while molecule 4 appears to gradually rotate from the red to the green direction between images (b) to (d) and back again to the red direction between images (e) to (h). Fast rotational activity is observed for molecule 6 with sudden fluctuations from one scan line to the other within the same image. Sudden appearances and disappearances of molecules are also observed. For instance, molecules 8 and 9 are only present from image (f) on, while molecules 3 and 6 have disappeared in image (h). Molecule 1 emits light in image (e), (f) and (h), but not in (g). This behavior is probably caused by a quantum-mechanical transition to a non-emitting molecular state. Finally, figure 5.4.13 (also on page 327) shows the time-resolved sliding of a repair-enzyme over a DNA chain.

Conclusions

Near-field scanning optical microscopy allows fluorescence, absorption and polarization contrast with nanometer lateral resolution, unlimited by diffraction. In particular, near-field fluorescence microscopy gives a clear high-resolution contrast and induces virtually no bleaching as opposed to conventional fluorescence microscopy. Shear-force feedback is essential for reliable operation of the aperture type based on fibers, especially while scanning over the soft surfaces of cells and chromosomes. The aperture-type near-field fluorescent microscope gives chemical specificity and orientational information in addition to the simultaneously acquired topographical image using force feedback. For bioscience, the technique offers a large potential for the structural and chemical analysis of cellular material and for the detection of molecular organization on membranes [van Hulst, 1997a]. Applications of photon tunneling microscopy are less numerous because this technique is limited to non-scattering surfaces. For further information on recent advances in the development and application of near-field optical microscopy the reader is referred to recent conference proceedings [Paesler, 1995; van Hulst, 1997b].

5.5 APPLICATIONS OF NANOSCALE-RESOLUTION MICROSCOPES

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5.5.1 THE SCANNING PROBE INDUSTRY

Compared to the other fields of nanotechnology, scanning probes are a relatively mature technology in the sense that there is already a strong scanning probe industry. The scanning probe industry mainly consists of (high-tech) small and medium enterprises (table 5.5.1). They are part of the scientific-instrument and process-control industry. The world market volume for commercial instruments amounted to \$200 million per year in 1997. In concrete numbers, there are roughly 100 commercial probes present in the Netherlands, with an average cost of \$100,000, and a write-off of 5 years; apparently our country represents 1% of the world market. The world market volume for home-made systems is estimated at an additional \$100 to 140 million. These numbers are much smaller than, for instance, for the semiconductor industry because their customers are universities and industries only.

Table 5.5.1

Some of the most important producers of scanning probes and tips.

company name	home country	market volume ¹⁶	website location
Digital Instruments	USA	\$51 M	http://www.di.com/
Park	USA	\$14 M	http://www.park.com/
Topometrix	USA	\$9 M	http://www.topometrix.com/
Burleigh Instruments	USA		http://www.burleigh.com/scan.htm
Molecular Imaging	USA		http://www.molec.com/
RHK Technology	USA		http://www.rhk-tech.com/
Olympus Optical	Japan		http://www.olympus.co.jp/indexE.html
JEOL	Japan		http://www.jeol.co.jp/index-E.htm
Nanonics	Israel		http://www.nanonics.co.il/
Omicron Instruments	Germany		http://www.omicron-instruments.com/index.html
Zeiss	Germany		http://www.zeiss.de/mi/rsm_e/rsm_e.html
Nanosensors	Germany		http://ourworld.compuserve.com/homepages/nanosensors/
NanoTools	Germany		http://nano-tools.com/
Oxford Instruments	UK		http://www.oxinst.com/ri/spm1.htm
NT-MDT	Russia		http://www.ntmdt.ru/
Total		\$ 200 million	

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¹⁶ private communication of R. Jobin, Park Scientific Instruments, Europe

The rapid development of scanning probe microscopes has definitely given a strong impetus to the development of nanoscale science and technology. Still, practical use is limited to analysis. Unless a breakthrough occurs in the speed of scanning probe lithography, their role in chip fabrication remains supporting. On the other hand, they may allow for high-storage density memories in the near future.

5.5.2 CURRENT APPLICATIONS OF SCANNING PROBES

After its invention in the early eighties, the development of the scanning probe microscopes has sped up due to their applicability. The atomic force microscope, especially, is now used more and more in industry, not only as a research tool but also as a quality-control tool. The overview of applications given here is primarily based on an excellent overview *Industrial uses of STM and AFM* [Vorburger, 1997]. Industrial applications of scanning near-field optical microscopy (SNOM) are still scarce.

Microelectronics

Probably the most widespread use of scanning force and tunneling microscopy is product inspection in the data storage industry. For instance, atomic force microscopy is used on-line in manufacturing to assess the roughness of the recording head-slider surface in magnetic disks, which requires nanometer-tolerances these days. The lateral resolution is an especially important advantage over traditional inspection techniques. Magnetic force sensing is an altogether new and important possibility. AFM is also of a key technology for assessing the quality of the pits in optical disks.

AFM and STM have also been used extensively in the semiconductor industry to determine the dimensions of the (steadily shrinking) circuit features. Manufacturers of integrated circuits – such as Philips – have discovered the versatility of the instrument, even in a production environment. The dedicated atomic force microscopes they use are fully automated and hardly need an operator to be present (figure 5.5.1). An example is imaging of the topography of feature side walls or the wafer roughness, sometimes done in-line during wafer processing. However, the low scanning speed is a real disadvantage, which is why the scanning electron microscope (SEM) is more widely used (figures 2.2.32-34).

Materials science

In the chemical industry, scanning probes are principally used to study surface morphology and to measure chemical and nanomechanical properties of polymers and coatings. As described in section 5.3.1., tapping-mode AFM measurements on soft materials such as polymers can be related to their stiffness and adhesion to a substrate. Using this information, the nanoscale morphology of a phase-separated mixture of polymers with different mechanical properties can

Figure 5.5.1

The Dimension 9000 AFM from Digital Instruments¹⁷ is the first fully automated AFM designed exclusively for in-fab semiconductor metrology, including robotic cassette-to-cassette handling for wafers up to 200 mm in diameter. Courtesy of Digital Instruments, Santa Barbara, CA.



be determined. The possibility of obtaining adhesive and chemical information was mentioned in section 5.3.2. An application of STM for basic industrial research is the study of atomic-scale restructuring during catalysis [Wilson, 1995]. Scanning probes are also used in the automotive, aerospace and related industries to determine the tribological interaction between components, the edge quality of tools, the hardness and related mechanical properties on (sub)micrometer length scales, the fine structure of machined and polished surfaces and the basic structures of industrially important materials.

Optics

Scanning probes are used for the determination of the surface roughness of optical components. Most applications are in research and development.

Electrochemical measurements

A striking application of both STM and AFM is the measurement of changes in surface structure during electrochemical reactions in solution, such as the progressive formation of atomic terraces or rapid etching. So far, the use is limited to research and development.

¹⁷ <http://www.di.com>

5.5.3 FUTURE IMPACT

Based on the mentioned applications and trends, the currently expected strategic relevance of scanning probe microscopes is the following: analysis of nanostructures, fabrication of prototype nanostructures, on- and off-line process control in industry, biosensors, data storage and possibly education. This section describes their expected future impact in some detail.

Analysis of nanostructures

In research – in industry as well as academia – scanning probe microscopes will be used to perform studies on the nanometer scale. Their strongest points are the ability to study dynamic processes and to study individual molecules interacting with the environment. Scanning probe microscopes are being used in many areas within physics, chemistry and biology, both in academic and in industrial laboratories. New technical developments in one type of application are quickly taken over in others. In this rapid development, they continue to provide a very fruitful breeding ground for innovation.

The imaging of surfaces of materials with atomic resolution using scanning tunneling microscopes allows detailed understanding of atomic-scale structures and processes on conducting substrates. This will prove necessary for the design of novel (electronic, chemical, mechanical) devices on that scale, and for the development of methods to fabricate them. It is of utmost importance to further develop scanning tunneling microscope technology in order to expand the range of environments in which this type of microscope can operate.

Atomic force microscopes will play an important role in the study of the properties of non-conducting substrates. For instance, the determination of the surface energy of a polymer film opens the possibility of developing nanosensors that are several orders of magnitude better than the existing ones [Vansco, 1998]. Groups working on mesoscopic devices need the technique to study those devices non-destructively. For biologists, the atomic force microscope will finally deliver its promise, namely studying biological processes in real-time at the nanometer scale. Both researchers and manufacturers of atomic force microscopes and tips will learn how to lower the interaction forces and how to increase the scan speed. Within ten years time, almost every biochemical research lab will use an atomic force microscope on a daily basis, just as they are doing now with optical and electron microscopes. New discoveries and inventions will be made in which techniques based on atomic force microscopy will play a key role. The development of chemical force methods is crucial to increase the possibilities of the technique even further. Magnetic force microscopes will prove very valuable tools for the development of nanostructured memories.

Near-field optical microscopy is gradually becoming mature and moving from the developmental stage towards applications. Its main current limitations are

complicated operation, loss of light and lateral resolution. The first commercial instruments have appeared on the market, yet their operation requires a rather specialized and experienced microscopist. The aperture probe brightness is sufficient for single molecular detection. Yet it is still rather little for spectroscopic applications such as fluorescence and Raman scattering, where lack of light limits the speed of imaging. The lateral resolution of 20 to 100 nm is almost an order of magnitude better than that of confocal microscopy, yet still rather poor compared to the resolution achieved with force microscopy. Ongoing research on probe fabrication through optimized fiber pulling and etching or micro-machining may result in future probes with higher efficiency, versatility and resolution.

Nanoscale-resolution far-field optical microscopes are expected to play an important role in the real-time study of nanoscale processes, which are especially relevant for the study of biological systems.

Nanofabrication of prototype structures

The capability of atomically manipulating and engineering surfaces ('atomic-scale construction kit') makes the scanning tunneling microscope a very useful tool for materials science by 'quickly' producing new 'prototype' atomic configurations and exploring their properties. This approach is close to a guarantee for new phenomena. Some of these surprises will undoubtedly find their way into future generations of high-tech devices depending on one or several nanoscale functional structures. A related application of scanning tunneling microscopes is the repair of nanoscale structures on a surface, such as a broken or damaged DNA string.

It seems natural to associate the future promise and strategic relevance of the scanning tunneling microscope primarily with the appealing manipulation techniques mentioned in section 5.2.3. With the ability to construct devices atom by atom, it seems that the ultimate level of miniaturization has been reached.

However, it is difficult to foresee to what extent these laboratory techniques can be scaled up into industrial technologies. It seems unlikely at this point that scanning tunneling microscopes or even scanning tunneling microscope-arrays will become capable of reliably producing large numbers of atomic-scale structures. Other methods, possibly relying on self-organization mechanisms, for instance exploiting special crystal growth kinetics or effects of stress and strain, will have to be developed for mass production of the selected useful structures.

Process control in industry

The use of scanning probe microscopes is currently restricted to large companies. It is expected that in the future smaller companies delivering high-quality products will also use such automated scanning probe microscopes to check the surface finish of their products on a routine basis. Atomic force microscopes

are increasingly being used by industry as a diagnostic off-line tool for manufacturing or even for on-line process control [Vorburger, 1997]. To a lesser extent, the same holds for scanning tunneling microscopes. In principle, near-field optical microscopes might become useful as a tool for process control, but this would have to be demonstrated first.

Biosensors

A special field of application for the analysis of nanostructures is that of biosensors. In particular chemical probe microscopes are expected to become suitable tools to analyze, for instance, the human genome. It is not difficult to imagine how such a device might work: place four tips behind each other, each one coated with one of the four bases that constitute the DNA molecule, pull the stretched DNA string underneath using an optical tweezer, correlate the four readings and one should find the base pair sequence.

Data storage

As described in section 1.2, near-field optics is already used for high-density data storage (20 Gbyte on 3.5-inch disks). For each bit, a light pulse heats the magnetic material in a 50-nm area above the Curie temperature, after which a miniature electromagnet changes the direction of magnetization. Depending on the date of their market introduction, this technology might form a serious competitor to hard disks.

Education

Three young postdocs from Basel, Switzerland have developed 'desktop STM' that can be operated on an ordinary table [Chapman, 1998]. Their aim is to use it for educational purposes, especially in high schools. Not only may it provide a new, big market for scanning tunneling microscopes, but it may also arouse the interest of the next generation for a career in (nano)science and technology.

Figure 5.4.12

Seven consecutive images of fluorescent single molecules (carbocyanine molecules dispersed in PMMA) using fluorescence near-field scanning optical microscopy. An area of $1.5 \times 1.5 \mu\text{m}^2$ is scanned in about 10 minutes, while simultaneously detecting two perpendicular polarizations of the single-molecule fluorescent light. The colors indicate the molecular orientation: green = signal in polarizer 1, red = signal in polarizer 2, yellow = signal in both polarizers. The 100-nm spatial resolution is limited by the probe aperture. (a) Shows the relative positions of the molecules, some of which are indicated by a number. Reprinted with permission from [Ruiter, 1997]. Copyright 1997 American Chemical Society. See page 319-320.

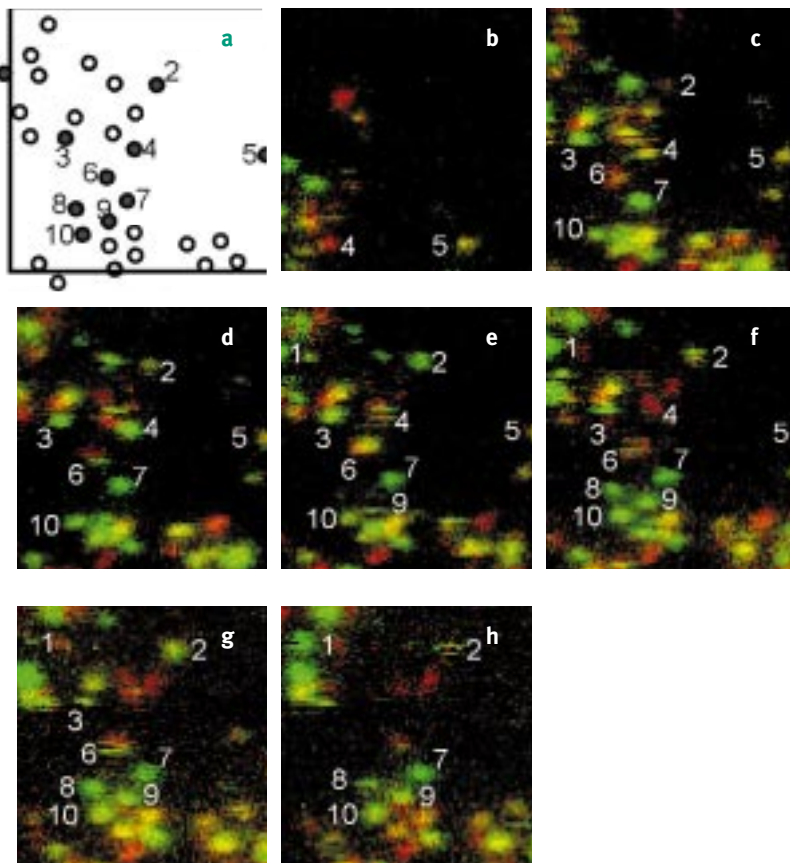


Figure 5.4.13

Sliding of photolyase over DNA. Photolyase is an enzyme from the *E. coli* bacteria that repairs ultraviolet-induced damage in DNA. **a** Frame 1-4 ($500 \times 500 \text{ nm}^2$, 1 frame per minute) show that the photolyase (white spot) slides over the DNA chain in the middle. This movement is not induced by the tip, which in fact scans in the opposite direction. The DNA is attached to the surface at some points only, which is why parts of the chain wiggle while the enzyme moves. **b** The averaged image (25 frames) show that the photolyase movement is restricted to the wiggling (fuzzy) parts. See page 319-320.

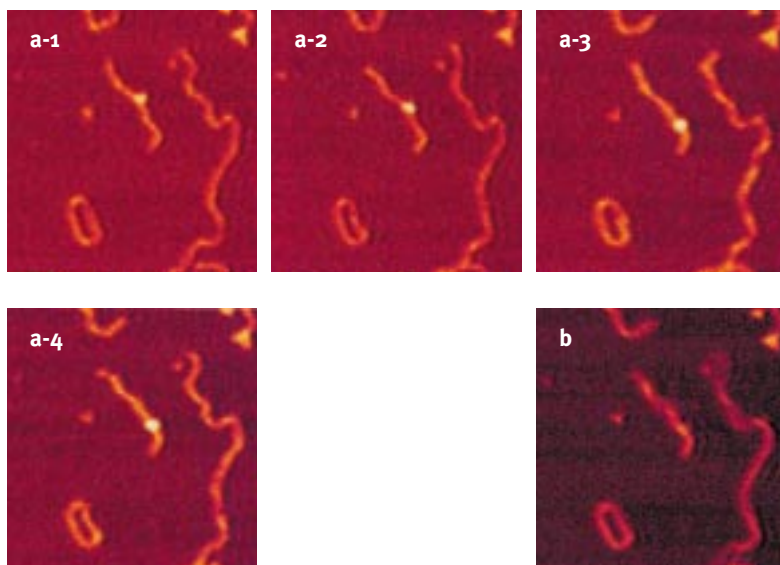


Figure 1.2.2

Artist's impression of a DNA chip. The Affymetrix chip contains 16,000 different cells of $93 \times 93 \mu\text{m}^2$. Every cell contains millions of identical oligonucleotide molecules that function as a gene probe. These molecules are applied using lithographic techniques similar to those used in the microelectronic industry. When a liquid containing diced genes from a human cell is poured over the chip, gene pieces whose sequence corresponds to that of a particular cell will mate to that oligonucleotide. Under a laser light, the probes that have found a match will glow. The location of glowing dots on the chip is detected using an optical microscope, and reveals which genes are present. See text on page 39 and further.

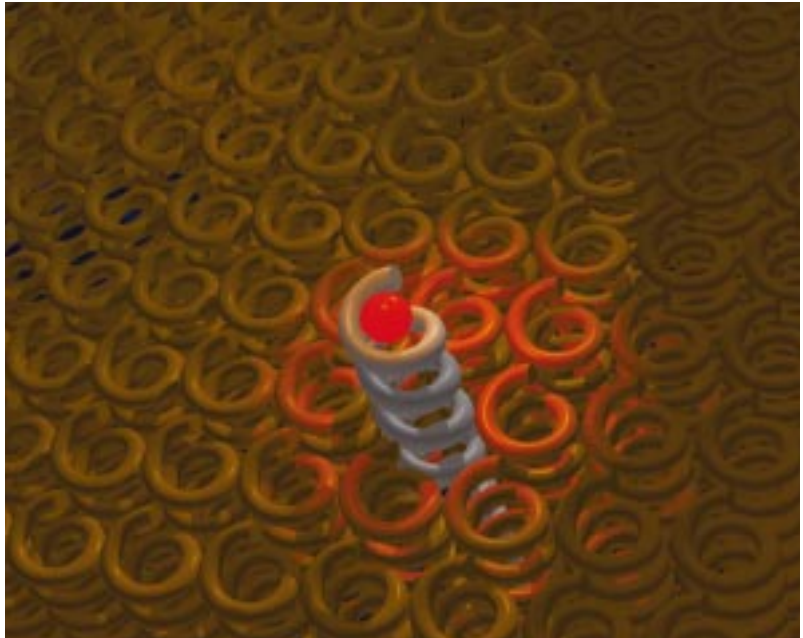


Figure 3.3.5

Artist's impression of a graffiti-repelling hybrid coating. The uncoated areas (right) are covered with paint. The coating (left) repels the paint so that it cannot adhere and forms drops to minimize the contact area with the surface. See text on page 168 and further.



5.6 WINDOW TO THE NANOWORLD

A. ten Wolde, J.W.M. Frenken^{18,19} and N.F. van Hulst²⁰

Scanning probe microscopes have developed into a family of useful tools for science and industry. Their applications have given rise to a strong scanning probe manufacturing industry. Scanning probe microscopes will have a strategic relevance for the study of nanostructures, the nanofabrication of prototype structures, on- and off-line process control in industry, and possibly education. The low scanning speed forms a major bottleneck for many other applications. The technology for parallel operation still needs to be proven. The main applications are diagnostics, biosensors, and a memory-reading device.

The STT workshop (appendix 1) led to the identification of the following research issues as being the most important:

- the development of chemically specific probes
- the development of truly atomic tips
- the development of arrays of tips
- addressing nanostructures (connecting the nanoworld with the real world).

In order to be able to quickly incorporate new technical and fundamental ‘nano-knowledge’ into future technologies, it is absolutely vital that new generations of specialists are trained, with academic as well as technical backgrounds, to construct and use scanning probe microscopes as well as the spin-off technologies emanating from this rapidly evolving field.

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21 <http://www.scanning-fams.org/>

22 [http://www.gbhap-us.com/
journals/293/](http://www.gbhap-us.com/journals/293/)

SOURCES

Magazines

- *Scanning, the Journal of Scanning Microscopies*²¹, FAMS, Mahwah, USA
- *Nanobiology*²², Gordon and Breach Science Publishers

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6

Conclusions and recommendations

MAIN CONCLUSION

Nanotechnology facilitates an increasing control over material structures. It will be a key technology in the 21st century and allow for the development of many applications in all product areas, starting with materials, electronics, and health care. Applications of nanomaterials have already been generated in various other areas such as cosmetics and skin care, pigments, coatings, and catalysts, and have the demonstrated potential to influence optics, energy technologies, the automobile industry, sensors, cutting tools, high-performance parts for the aerospace and the building industry, packaging foils, and (opto)electronics. High-storage-density memories using scanning probe surface modification represent immediate industrial opportunities. In the long term, molecular manufacturing of macroscopic products using Drexler's nanomachines could be realized, but the drastic reduction of manufacturing cost required for a revolution of our economic structure is not foreseen.

RECOMMENDATIONS

Governments

- Appoint a coordinator for the – fragmented – research programs in different areas of nanotechnology.
- Continue to stimulate network formation and interdisciplinary research in the area of nanotechnology to enable scientific and application-oriented public-private cross-fertilization.

Universities

- Offer educational programs including appropriate fields of nanotechnology.

Scientists

- Participate in networks and interdisciplinary research.

Existing industries

- Keep a close watch on the development of small, innovative high-tech companies in the area of nanotechnology relevant to your industry.
- Invest in startup companies.
- Create incubation centers!

Media

- Start broadcasting programs on nanotechnology, and explain the scientific developments in understandable terms to a wide audience.

Venture capitalists and pioneers

- Invest in near-term applications, but don't forget that high-risk investment in long-term developments may be much more profitable.
- Entrepreneurs, start your nanotechnology company now!

Appendix 1

REPORT OF THE WORKSHOP 'INDUSTRIAL APPLICATIONS OF NANOTECHNOLOGY'

A. ten Wolde

This workshop was held on 15 January 1998, in Utrecht, the Netherlands. The organization of this day turned out well. The attendance was good: 44 participants, including 15 participants from companies and several policy makers; 19 participants came from outside the task forces.

INTRODUCTORY LECTURES

George Robillard (University of Groningen) presented an introduction on top-down and bottom-up nanotechnology. As applications he mentioned for example nanoelectronic devices, polymers, molecular receptors and molecular switches for optical data storage. Helmut Schmidt of the German Institut für Neue Materialien (INM) lectured on the development of applications based on nanopowders and nanostructured materials. Examples were plastic lenses, crash-resistant plastic glasses, anticorrosion coating, nano-coated foil and fire-resistant glass (figures 3.10.1-2).

ACTIVE SESSION

The next item was an active workshop session led by René Tol and Gerbert Rebel from the Management Informatie Centrum, using the so-called metaplan method. The participants were qualified – on basis of their knowledge – as an expert in one of the four fields of nanotechnology (see below) or as a generalist. They then spread among seven mixed – very multidisciplinary! – groups for discussion about one of the four fields, under guidance of an expert.

The following conclusions came forward:

Nanoelectronics

- The costs of the development of nanoelectronics form an obstacle. For example, further miniaturization requires switching to a new lithographic technique while the added value is decreasing.
- The nanoscale allows new devices such as one-electron transistors or the resonant-tunneling transistor, and new principles such as multivalued logic.
- Bottom-up (chemistry) methods are meeting top-down (lithography): maybe chemistry can help to keep down the costs of nanostructuring.
- Electronics is the market pull behind nanotechnology; however, this one-sidedness threatens the development of the technology.

Nanomaterials

- The applications mentioned by Schmidt give a nice overview.
- Solar cells form an interesting niche market. Hybrid materials and new ceramic materials form important applications.
- Kemira already produces about 50 tons of nanostructured titanium dioxide per day, to be used (for example) for paint and sunburn lotion.
- Working with nanoparticles is not an everyday occupation. Health and safety deserve special attention.
- The nanoscale offers many opportunities for materials and devices with new properties due to surface enhancement and quantum effects.

- Material defects play a more important role on the nanoscale than in larger scaled objects.
- It is unclear if multidisciplinary research needs (still) more or (adversely) less stimulation.

Molecular nanotechnology

- It is still very early to discuss the impact of molecular nanotechnology on society, such as the consequences for employment.
- Nature offers important examples for new nanostructures (biomaterials) and processes (photosynthesis). ‘Biomimetics’ are mainly interesting for medical applications, less for industrial processes.

Nanoscale microscopes

- Besides scanning probe microscopes, other techniques such as transmission electron microscopy and x-ray microscopy belong to this field as well.
- For many applications, scanning probes are too slow.
- The technology for parallel writing still needs to be proven.
- Applications: diagnostics, biosensors, memory-reading device.
- Important: development of chemically specific probes, truly atomic tips, connecting the nanoworld with the real world.
- The link with the industry was not made, but does exist.

Questions for Merkle

After the workshop session, Ralph Merkle of Rank Xerox lectured and answered questions through a live videoconferencing connection from Palo Alto (California) with Media Plaza (Utrecht). He stated that safety and health hazards of nanoparticles can be controlled well, and that Heisenberg’s uncertainty principle poses no fundamental obstacle for the precise (dis)placement of individual atoms in a nanostructure.

The participants during the introductory lectures.



Group discussion on nanoscale microscopes led by task force chairman Niek van Hulst.



Steering committee chairman David Reinhoudt summarizes the conclusions.



David Reinhoudt (to the right) confers by video conferencing from Media Plaza (Utrecht, the Netherlands) with Ralph Merkle in Palo Alto (California, not in the picture); to the left Michiel Westermann and Arthur ten Wolde (fully left).



Appendix 2

APPLICATIONS

enabling technology	product area	product example	time to market (years)	
nanomaterials technology	electronics	chips with 25 million transistors/cm ²	5	
	optics	scratch-resistant spectacles	0-5	
	catalysts	photocatalytic air purifier	0-5	
	energy	organic solar cell	5-15	
	automobile industry	corrosion protection	5-10	
	sensors	smoke detectors	0-5	
	medicine	biocompatible materials	5-10	
	cutting tools	ultrastrong tools	5-10	
	aerospace industry	high-performance parts	5-10	
	building industry	high-performance parts	5-10	
	electronics	resistors and varistors	5-10	
	optoelectronics	high-definition television screens	10-20	
	military	fast-burning powders	5-10	
	molecular nanotechnology	medical	biochip arrays	0
			drug carrying liposomes	10-20
		biomolecular sensors	10-20	
electronics		smart cards	5-10	
		flat panel displays	5-15	
		biomolecular processing chips	20-30	
materials		fullerenes	0	
catalysts		dendrimers	5-15	
energy		molecular solar cells	5-15	
molecular machines		molecular assemblers	20-30	
scanning probes	nano-microscopes	tunneling, force and near-field	0	
	electronics	20-gigabyte memory on a 3.5-inch floppy	1-10	

Some present and future applications of nanotechnology. The years to market introduction should be interpreted as an indication only.

Appendix 3

PERIODIC TABLE OF ELEMENTS

15	1	2
	H Hydrogen	He Helium

13	14	15	16	17	18
5	6	7	8	9	10
B Boron	C Carbon	N Nitrogen	O Oxygen	F Fluorine	Ne Neon
13	14	15	16	17	18
Al Aluminum	Si Silicon	P Phosphorus	S Sulfur	Cl Chlorine	Ar Argon
31	32	33	34	35	36
Ga Gallium	Ge Germanium	As Arsenic	Se Selenium	Br Bromine	Kr Krypton
49	50	51	52	53	54
In Indium	Sn Tin	Sb Antimony	Te Tellurium	I Iodine	Xe Xenon
81	82	83	84	85	86
Tl Thallium	Pb Lead	Bi Bismuth	Po Polonium	At Astatine	Rn Radon

11	12	13	14	15	16	17	18	19	20
3	4	5	6	7	8	9	10	11	12
Li Lithium	Be Beryllium	B Boron	C Carbon	N Nitrogen	O Oxygen	F Fluorine	Ne Neon	Na Sodium	Mg Magnesium
11	12	13	14	15	16	17	18	19	20
Na Sodium	Mg Magnesium	Al Aluminum	Si Silicon	P Phosphorus	S Sulfur	Cl Chlorine	Ar Argon	K Potassium	Ca Calcium
37	38	39	40	41	42	43	44	45	46
Rb Rubidium	Sr Strontium	Y Yttrium	Zr Zirconium	Nb Niobium	Mo Molybdenum	Tc Technetium	Ru Ruthenium	Rh Rhodium	Pd Palladium
55	56	71	72	73	74	75	76	77	78
Cs Cesium	Ba Barium	Lu Lutetium	Hf Hafnium	Ta Tantalum	W Tungsten	Re Rhenium	Os Osmium	Ir Iridium	Pt Platinum
87	88	103	104	105	106	107	108	109	
Fr Francium	Ra Radium	Lu Lutetium							

57	58	59	60	61	62	63	64	65	66	67	68	69	70
La Lanthanum	Ce Cerium	Pr Praseodymium	Nd Neodymium	Pm Promethium	Sm Samarium	Eu Europium	Gd Gadolinium	Tb Terbium	Dy Dysprosium	Ho Holmium	Er Erbium	Tm Thulium	Yb Ytterbium
89	90	91	92	93	94	95	96	97	98	99	100	101	102
Ac Actinium	Th Thorium	Pa Protactinium	U Uranium	Np Neptunium	Pu Plutonium	Am Americium	Cm Curium	Bk Berkelium	Cf Californium	Es Einsteinium	Fm Fermium	Md Mendelevium	No Nobelium

Survey organization

This publication was realized with the active help of 69 nanotechnology experts. STT wishes to express its gratitude to all those who donated their time and energy to this study project. A steering committee was set up to determine the precise line of approach and to guard the academic content of this study project. The advisory board was regularly consulted to assure input from outside Europe. The four task forces have each produced a chapter of the book.

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The study project was managed by Arthur ten Wolde, project manager STT. STT-director F.J.G. van de Linde not only helped the project manager with the conceptual framework around the study project, but also played an active role in the set-up of the seminars and the formation of the Platform Nanotechnology. Rosemarijke Otten, project secretary at STT, cooperated in the organization of the study project.

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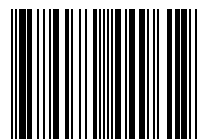
Nanotechnology is considered a key technology for the 21st century by renowned scientists. But what exactly is nanotechnology? What is the difference between 'bottom-up' and 'top-down' nanofabrication, and what is a scanning probe microscope? And most of all: what will nanotechnology bring us?

These questions are addressed in this book from the Netherlands Study Centre for Technology Trends (STT). It uses terms that are understandable to a wide technically interested audience. It provides an overview of the scientific state of the art as well as the technological potential of nanomaterials, nanoelectronics, molecular nanotechnology and nanoscale-resolution microscopes. The impact is illustrated with examples of current and future applications in almost every product area.

This book is a special jubilee edition to celebrate STT's 30th anniversary. It is the tangible result of a collaborative effort from STT and many scientists from universities and industry with backgrounds in physics, chemistry and biology. This publication is intended for everyone involved in technological development, and especially for those interested in this wave of innovation surpassing the impact of information technology and biotechnology.



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