EUROPEAN COMMISSION

Community research

Nanotechnology
Innovation for tomorrow's world

NANOTECHNOLOGIES AND NANOSCIENCES,
KNOWLEDGE-BASED MULTIFUNCTIONAL MATERIALS,
AND NEW PRODUCTION PROCESSES AND DEVICES

GENERAL INFORMATION

Interested in European research?

RTD info is our quarterly magazine keeping you in touch with main developments (results, programmes, events, etc.). It is available in English, French and German. A free sample copy or free subscription can be obtained from:

European Commission
Directorate-General for Research
Information and Communication Unit
B-1049 Brussels
Fax (32-2) 29-58220
E-mail: research@cec.eu.int
Internet: http://europa.eu.int/comm/research/rtdinfo/index_en.html

Editor: EUROPEAN COMMISSION

Directorate-General for Research
Directorate G — Industrial Technologies
Unit G.4 — Nanosciences and Nanotechnologies

Contacts: Dr. Renzo Tomellini, Dr. Angela Hullmann

E-mails: *renzo.tomellini@cec.eu.int*, *angela.hullmann@cec.eu.int*

Url: www.cordis.lu/nanotechnology

EUROPEAN COMMISSION

Nanotechnology

Innovation for tomorrow's world

This brochure originates from a project funded by the German Federal Ministry for Education and Research (BMBF) and that was carried out by the German Association of Engineers - Technology Centre (VDI-TZ). The European Commission is grateful to the BMBF for granting permission to translate this publication and make it available to the European public. Special thanks are due to Dr. Rosita Cottone (BMBF) and Dr. Wolfgang Luther (VDI-TZ) for their assistance with coordination.

Bundesministerium für Bildung und Forschung

At the time-being, this brochure is only available in English and in the German original version. Translations in Czech, Danish, Dutch, Estonian, Finnish, French, Greek, Italian, Hungarian, Lithuanian, Latvian, Maltese, Polish, Portuguese, Slovakian, Slovenian, Spanish and Swedish language will be published as pdf versions on the website www.cordis.lu/nanotechnology, as soon as they are available.

For the German original version see http://www.bmbf.de/de/nanotechnologie.php.

Published by: European Commission, Research DG

Produced by: Bundesministerium für Bildung und Forschung BMBF, Berlin

Coordination: Future Technologies Division, VDI Technologiezentrum GmbH, Düsseldorf

Author: Dr. Mathias Schulenburg, Cologne

Layout: Suzy Coppens, BergerhofStudios, Cologne

Printing: Druckhaus Locher GmbH, Cologne

Directorate-General for Research
« Nanosciences and Nanotechnologies »

2004

EUR 21151EN

Europe Direct is a service to help you find answers to your questions about the European Union

Freephone number:
00800 6 7 8 9 10 11

LEGAL NOTICE

Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of the following information.

The views expressed in this publication are the sole responsibility of the author and do not necessarily reflect the views of the European Commission.

A great deal of additional information on the European Union is available on the Internet.
It can be accessed through the Europa server (http://europa.eu.int).

Cataloguing data can be found at the end of this publication.

Luxembourg: Office for Official Publications of the European Communities, 2004

ISBN 92-894-7498-X

Printed in Germany

PRINTED ON WHITE CHLORINE-FREE PAPER

Foreword

Nanotechnology is a new approach that refers to understanding and mastering the properties of matter at the nano-scale: one nano-meter (one billionth of meter) is the length of a small molecule. At this level, matter exhibits different and often amazing properties and the borders between established scientific and technical disciplines fade. Hence the strong interdisciplinary character that is associated with nanotechnology.

Nanotechnology is often described as having a “disruptive” or “revolutionary” potential in terms of its possible impact on industrial production routes. Nanotechnology offers possible solutions to many current problems by means of smaller, lighter, faster and better performing materials, components and systems. This opens up new opportunities for wealth creation and employment. Nanotechnology is also expected to make some essential contributions to solving global and environmental challenges by realising more specific-to-use products and processes, save resources and lower waste and emissions.

Currently, enormous progress is being made in the worldwide nanotechnological race. Europe invested early with many programmes in nanosciences starting during the mid- to late-1990’s. It has subsequently developed a strong knowledge-base and now needs to ensure that European industry and society can reap the benefits of this knowledge through the development of new products and processes.

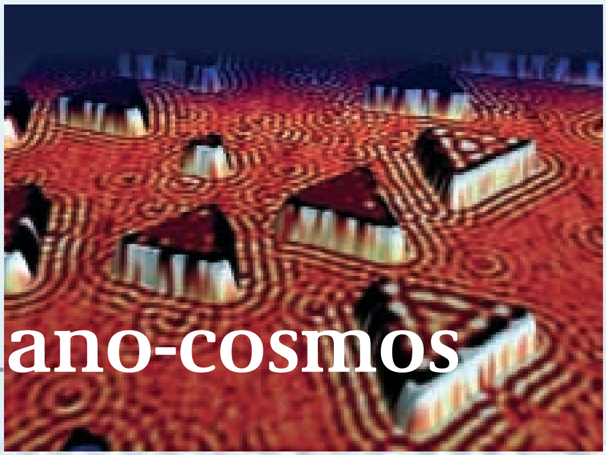
Nanotechnology is the subject of a recent Commission communication (‘Towards a European strategy for nanotechnology’). In this Communication, it is not only proposed that research in nanosciences and nanotechnologies should be boosted, but that several other interdependent dynamics must be taken into account:

- Greater coordination of national research programmes and investment also to ensure that Europe has teams and infrastructures (“poles of excellence”) that can compete at international-level. In parallel, collaboration between research organisations in the public and private sector across Europe is essential for achieving sufficient critical mass.
- Other competitiveness factors should not be overlooked, such as adequate metrology, regulations and intellectual property rights so as to pave the way for industrial innovation to be carried out and lead to competitive advantages, both for large and small- and medium-sized companies.
- Activities related to education and training are of great importance; in particular, there is scope in Europe to improve the entrepreneurial character of researchers as well as the production engineers’ positive attitude to change. The realisation of true interdisciplinary research in nanotechnology may also require new approaches to education and training for research and industry.
- Social aspects (such as public information and communication, health and environmental issues, and risk assessment) are further key factors to ensure the responsible development of nanotechnology and that it meets people’s expectations. Public and investors’ confidence in nanotechnology will be crucial for its long-term development and fruitful application.

The aim of this brochure is to illustrate what nanotechnology is and what it can offer to the European citizens.

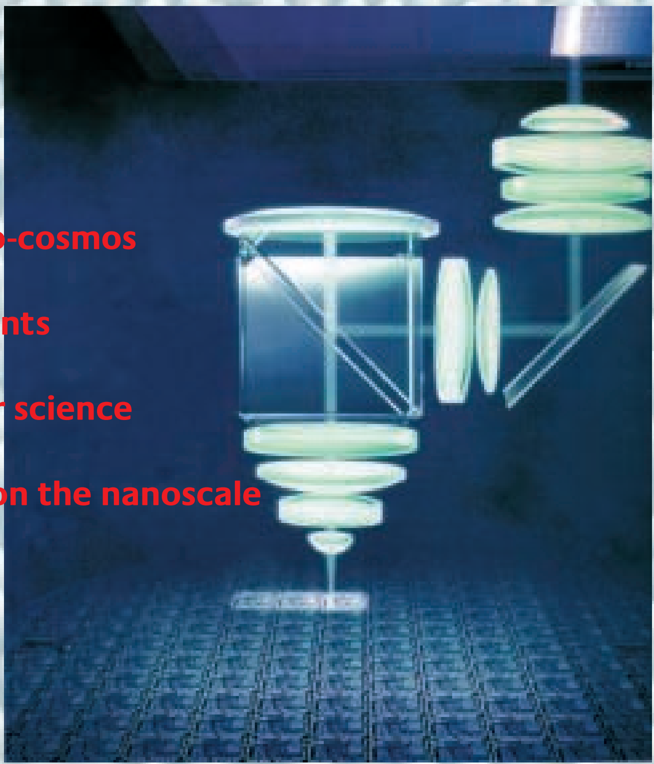
Ezio Andreta
Director “Industrial Technologies”
Research Directorate-general
European Commission

Contents



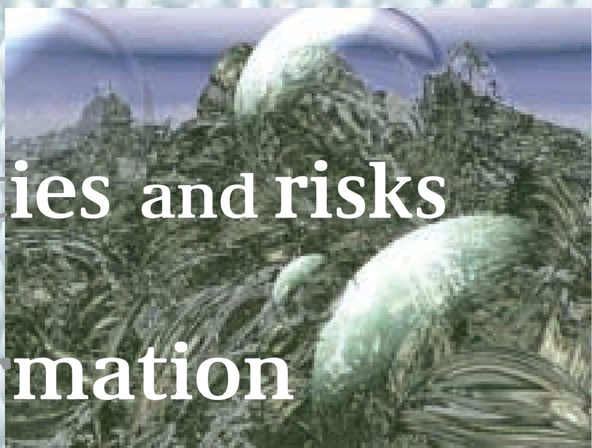
Journey into the nano-cosmos

Instruments and processes



Nanotechnology in society

Visions

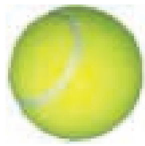


Opportunities and risks

Further information

Journey into the nano-cosmos

The atom: old idea and the new reality



The ratio of the diameter of a magnesium atom to a tennis ball is the same as that of a tennis ball to the Earth. Just think of that when you next take a magnesium tablet!

Amedeo Avogadro (1776-1856), a physics professor in Turin, the first man to analyse a raindrop.

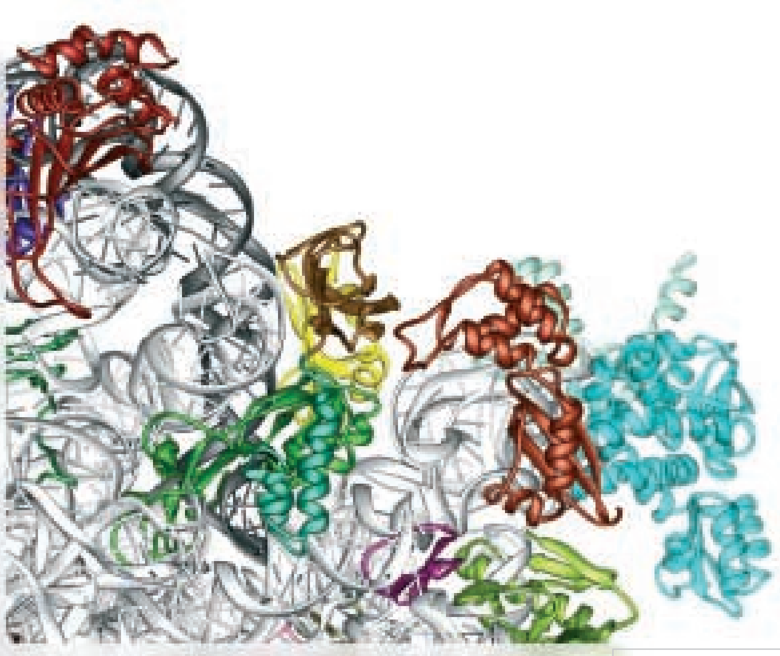
Our material world is made up of atoms. This was the claim made over 2 400 years ago by the Greek philosopher Democratus. The modern Greeks expressed their thanks by stamping his effigy on their 10-Drachma coin. This was in wide circulation, although not in the same numbers as atoms. A single raindrop contains about 1 000 000 000 000 000 000 000 of them, for atoms are miniscule – only one tenth of a nanometre in size, and a nanometre measures a mere one-millionth of a millimetre.

The spirit of Democratus hangs over the nano-scene, a sea of infinite possibilities.

A few centuries later, Lucretius, a Roman writer, wrote a poem about atoms: *"The Universe consists of infinite space and an infinite number of irreducible particles, atoms, whose variety is equally infinite. … Atoms vary only in shape, size and weight; they are impenetrably hard, unchanging, the limit of physical divisibility …"*

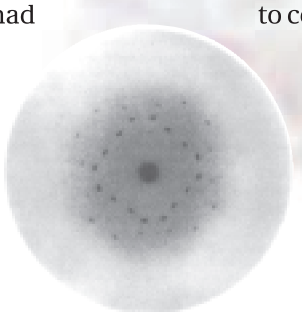
This was all very well, although it was at that point nothing more than pure speculation. For a long time, no more thought was given to such matters.

In the 17th century, Johannes Kepler, the famous astronomer, devoted thought to snowflakes, and published his ideas in 1611: the regular shape could only be due to simple, uniform building blocks. The idea of the atom again began to attract popularity.



The structure of biological nanomachines like ribosomes are crystallographically determined by Ada Yonath, DESY, Hamburg.

Scientists who worked with minerals and crystals took the existence of atoms as granted. In 1912 however, direct proof was obtained at the University of Munich: a copper sulphate crystal split up x-ray light in the same way that the material of an umbrella splits up the light from a lantern – the crystal had to consist of atoms, arranged in an ordered structure, like the yarn in umbrella material, or a pile of oranges in a market.



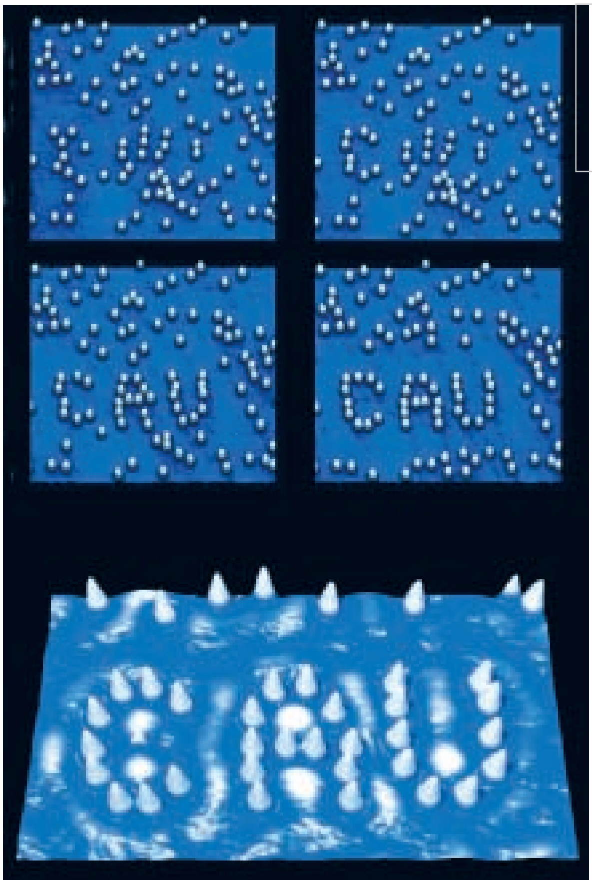
The reason why the atoms in the crystal arrange themselves so regularly is simple. The matter makes itself as comfortable as possible, and the most comfortable way is a regular, ordered structure. Even nuts shaken in a bowl form regular patterns, and this process is even easier for atoms.

Simple patterns are however not always the ones that are most easily reproducible. Driven by forces of self-arrangement, the matter of the Earth has over billions of years taken on a fantastically complex and, in some cases, even living form.

Modern analytical devices can now visualise such highly complex components of living matter down to a scale of nanometres.

Finally, in the 1980s, an instrument was developed, known as the scanning tunnel microscope, that can not only visualise the individual atoms within a crystal – many people considered the first images to be a hoax – but can also poke and prod them around.

The stage was now set for a radical new departure: nanotechnology.



Manganese atoms are used by Professor Berndt in Kiel to reproduce the logo of the Christian-Albrechts University.

Journey into the nano-cosmos

Nanotechnology in nature

Nanotechnologists hold living nature dear to their hearts. In the four billion years of its existence, nature has created some astounding solutions to the problems it has encountered. One typical feature: life structures its matter down to the finest detail, right down to the level of the atom. This is what nanotechnologists also aim to do.

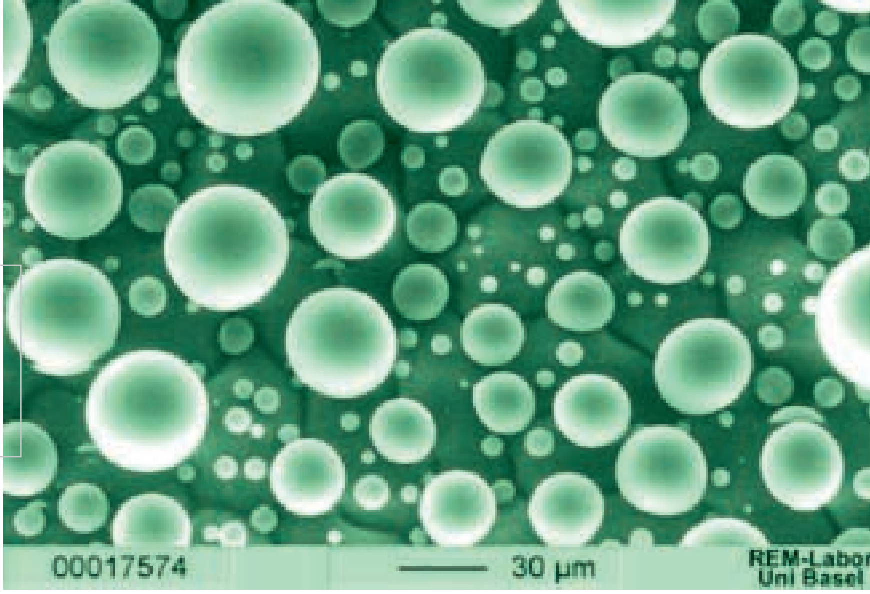
Atoms are not generally loved. When we hear about them, we tend to think of terrible explosions or dangerous radiation. But this only refers to technologies involving the atomic *nucleus*. Nanotechnology is concerned with the *shell* of the atom, this is the scale at which nanotechnology comes into play.

In order to remove any doubt we might have that atoms are everyday things, which in the right combination can even taste good, let us take as our point of departure into the nano-cosmos a mundane item such as cheese.

Mimolette is a product of Flanders and the tiny holes in the surface gives away the cheese's secret: it is inhabited! The producers recognise that the activity of the mites improve the aroma of Mimolette cheese. The mites are about a tenth of a millimetre in size. The ESEM (Environmental Scanning Electron Microscope), a special scanning electron microscope, can view even living mites. Like other living things, mites are also composed of cells. The scale of the cell is the micrometer. A cell is equipped with highly complex machinery. An important component of this machinery is represented by the ribosomes, which produce all possible protein molecules according to the specifications of the genetic material DNA. The order of size of the ribosome is around 20 nanometres. Parts of the ribosome structure have now been identified down to the level of individual atoms. The first fruits of this type of nanobiotechnology research have already been harvested in the form of new medications capable of blocking bacterial ribosomes.

The lotus blossom cleans its leaves with the aid of the eponymous lotus effect.

Water droplets on a nasturtium leaf, imaged with the aid of the Environmental Scanning Electron Microscope (ESEM).

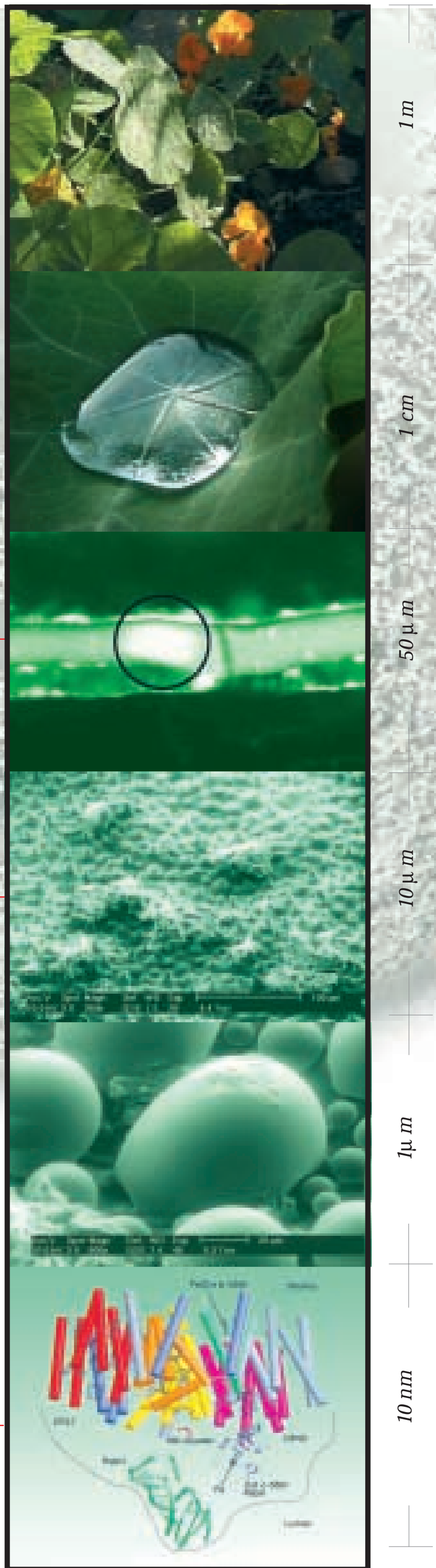


Lotus effect & Co.

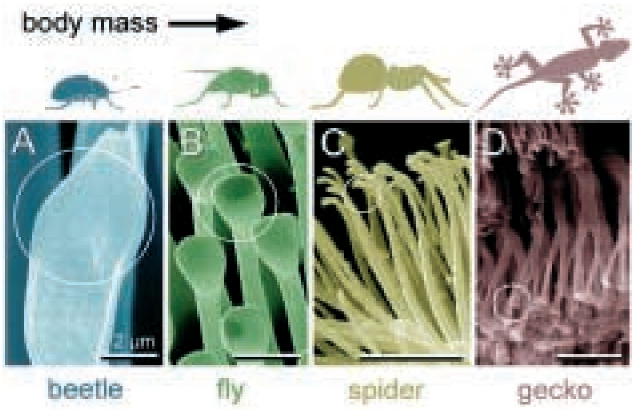
The nasturtium keeps its leaves clean with the aid of the lotus effect. The ESEM Environmental Scanning Electron Microscope shows how water droplets are kept away from the surface of the leaf. This is due to the downy surface of the leaves that causes the water droplets to run off at high speed, taking with them any dirt on the surface of the leaf. The lotus effect, which has been researched extensively by Professor Barthlott and his associates at the University of Bonn, has already been used in a range of products, such as façade coatings, where the water runs off carrying away dirt. Sanitary ceramics that utilise the lotus effect are very easy to keep clean.

Plant leaves also make use of other types of nanotechnology. Their water management system is often controlled by forisomes, microscopically small muscles, which open up channels in the capillary system of the plant, or close them off if the plant is injured. Three Fraunhofer institutes and the University of Giessen are currently trying to develop technical applications for plant muscles, such as microscopically small linear motors, or perhaps a complete laboratory-on-a-chip (lab-on-a-chip).

One of the most refined technology on an atomic scale is the photosynthesis process, which collects the energy for life on Earth. This is a matter for every individual atom. Whoever can copy it using nanotechnology will have unlimited energy for all time.



Nanotechnology in nature



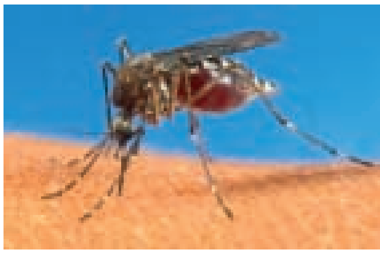
Nanotechnology on the ceiling: the gecko

Geckos can run up any wall, run upside down across the ceiling, and even hang from it by a single foot. This is done with the aid of – you guessed it – nanotechnology. The gecko's foot is covered in very fine hairs that approach the surface to within a few nanometres over large areas. This allows the so-called van-der-Waals bond to come into action and despite the fact that it is actually very weak, it supports the gecko's weight due to the millions of adhesion points. The bonds can easily be broken by "peeling", in the same way that one removes a strip of adhesive tape, allowing the gecko to run along the ceiling. Material scientists are already looking forward to producing a synthetic "gecko".

Beetles, flies, spiders and geckos have revealed some of the secrets of their sticking powers at the Max-Planck Institute for Metal Research in Stuttgart. They hold on by means of tiny hairs that form a van-der-Waals bond with the surface they are in contact with. The heavier the animal, the finer and more numerous are the hairs.

Sticking to life

Life exists because its components are held together by sophisticated nanotechnological adhesion methods. Even in the case of injuries, such as an insect sting: the point of the sting turns red, because tiny blood vessels expand, through which swarms of leukocytes, or white blood corpuscles then flow. Cells at the sting point secrete a pheromone. Depending on its concentration the cell linings of the blood vessels and the leukocytes deliver adhesive molecules, which delay the passage of the leukocytes along the vessel wall by their adhesive effect. At the maximum pheromone level, the leukocytes stick firmly; other adhesive molecules then draw the blood corpuscles through the vessel wall to the point of the sting, where they attack any intruders – the art of perfect adhesion. Man-made nanotechnological imitations are now being researched under the heading of "bonding on command".



Close-up of a fly's foot

Mussels – masters of the art of bonding

The common mussel – as cooked with vegetables and eaten every day in restaurants – is a master of the art of nanotechnological bonding. When it wants to attach itself to a rock, it opens its shell and pushes its foot onto the rock, arches its foot to form a suction cup, and injects streams of adhesives droplets, micelles, into the low-pressure area through tiny cannulae, where they burst to release a powerful underwater adhesive. This immediately creates a foam that serves as a small cushion. The mussel then anchors itself to this shock absorber with elastic byssus threads, so that it can be tossed about by the tide without harm.

Mussel with byssus threads and foot

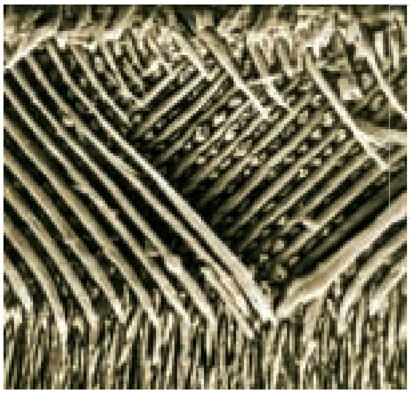
The Fraunhofer Institute IFAM in Bremen is researching into modified mussel adhesives, with which it hopes to make even the finest bone china dishwasher-proof. The "New materials and biomaterials" working group in Rostock and Greifswald also has mussels under the microscope.

Biomineralisation

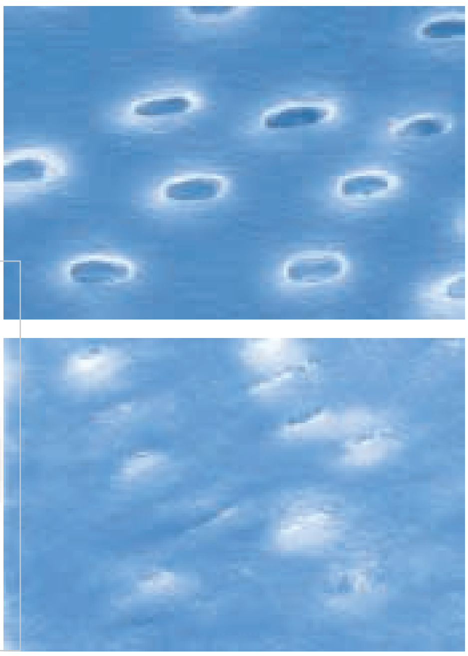
Mussels are capable of even more. Their mother-of-pearl consists of innumerable minute chalk crystals in the form of the mineral aragonite, which on their own would be very brittle. In the mussel however, they are held together by screw-shaped, highly elastic proteins. Three percent by weight of protein is more than enough to make the shell of the abalone mussel three thousand times tougher than a pure calcite crystal. Sea urchins also use this technique to strengthen their 30-cm long spines so that they can withstand the pummelling of the waves.

Biomineralisation can also create very delicate structures. On a small part of the ocean floor close to the Philippine Islands lives a sponge called the "Venus flower basket". This creature is curved like the sheath of a Turkish dagger, but circular around its long axis. The sponge owes its name to the structure of the inner skeleton of its mantle. This consists of a tissue of fine silica needles, perforated like the wickerwork of a wooden chair back. This tissue is interwoven both in a right-angled network and diagonally. The Venus flower basket is considered a masterpiece of biomineralisation: tiny elementary building blocks of silica (silicon dioxide) three nanometres in diameter first connect the cells of the sponge together in superfine layers. These are then rolled up to form the silica needles, the basic element of the wickerwork structure, which can withstand high pressure variations.

The Venus flower basket – this deep-sea sponge is currently being studied as a biological model for fibre-optics.



The three-dimensional biomineral network in the tooth enamel of the vole's molars protects the working surface against damage.



Technical biomineralisation: Nanoparticles repair teeth

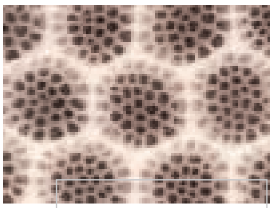
If teeth are very sensitive to cold or bitter foods this can cause pain and is usually due to tiny channels – open dentine tubuli – in the tooth enamel. With nanoparticles of calcium phosphate (apatite) and protein produced by the firm of SusTech, these channels can be closed off ten times quicker than with conventional apatite compounds. The remineralised material layer behaves just like the body's own tooth enamel in the mouth.

Nanotechnology in nature

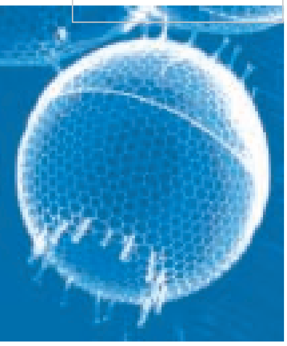
The starfish „Ophiocoma wendtii“ is equipped with a perfect micro-lens system for optical vision. Above: its appearance in daytime, and below: at night.

Of (formerly) strategic importance was the bio-mineralisation of diatoms. These microscopically small creatures protect themselves by means of a silicic acid shell, whose main component is SiO_2, or silicon dioxide. Like quartz glass, which also consists of silicon dioxide, silicic acid shells are also relatively resistant to many corrosive acid and alkaline solutions, which is why nanotechnologists hope to use them as reaction vessels for nanometre-size crystals. One trick for creating nanoparticles by chemical reactions is to limit the reaction volume. When the reaction material within is used up, the crystals created by the reaction remain small. Diatoms contain many such nanoscale pores, or nano-reactors.

How do these sometimes very visually-attractive diatoms come into existence? The first clues have been found. Researchers at the University of Regensburg have discovered that members of a well-known protein group, the "polyamines", can produce nanoparticles, in the right silicic acid concentration, with a controllable diameter of between 50 and 900 nanometres – quite spontaneously under the forces of self-arrangement. According to simple growth models, diatoms occur just as spontaneously.



Diatoms – above similar to a "Menger sponge" (see also p. 21) – have maximum stability with the lowest weight due to their optimum shapes and – probably – light-collecting systems for their photosynthesis apparatus, chloroplasts.

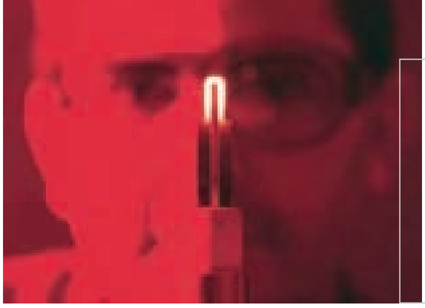


Why were diatoms supposed at one time to have had "strategic importance"? In 1867, the Swede Alfred Nobel discovered that infusorial earth, diatomaceous earth from fossil deposits of diatoms, absorbed nitroglycerine, thereby inhibiting the tendency of this explosive to detonate spontaneously. Nobel gave this mixture the name "Dynamite", whose roaring sales laid the basis for the foundation which today finances the Nobel Prizes.

Armoured scales and micro-lenses in one

Nanotechnology in nature: *Ophiocoma wendtii*, a plate-sized hairy star, presented a puzzle for a long time. This creature, from whose disc-shaped armoured body five arms extend, hurries into cover at the approach of potential enemies, although it apparently does not have any eyes. These were eventually found in the creature's armoured shell, which is studded all over with perfect micro-lens fields, turning the whole body of the hairy star into one complex eye. The nanotechnology? The individual lenses are crystallised in such a way that the characteristic of calcite to create a double image does not come into play – crystallisation control at the nanometre level. The lenses are also corrected for "spherical aberration" by the subtle addition of magnesium, in order to prevent undesirable colour fringes. Ophiocoma therefore uses nanotechnological refinements that once helped Carl Zeiss to achieve fame.

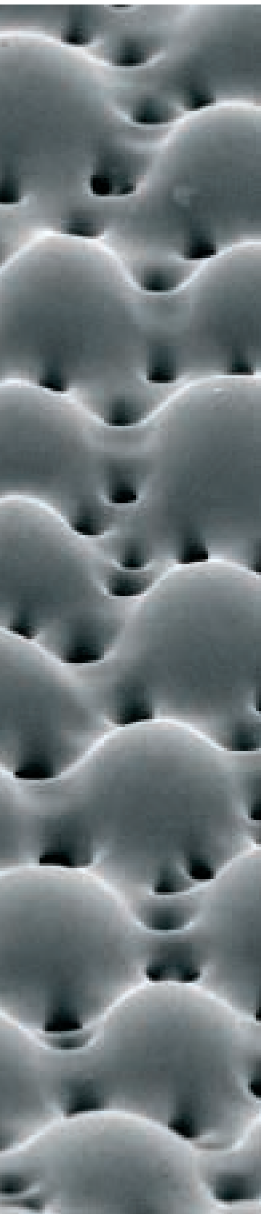
The Institute for New Materials (INM) in Saarbrücken has developed nanoparticle processes for applying counterfeit-proof, wear-resistant holograms to metal components.



Even nature cannot do this: ceramics treated with nano-soot for corrosion-proof glow-ignition systems, such as for gas heaters. The adjustable conductivity of the ceramics avoids the need for a transformer.

Exploring the limits of nature

Nanotechnology is based upon pure nature: yet the capabilities of living nature are restricted, it cannot work at either high temperatures, such as those needed for ceramics, or with metallic conductors. Modern technology on the other hand has a wide range of artificial conditions available – extreme purity, cold, vacuum – under which matter reveals some surprising properties. These include, in particular, quantum effects, which sometimes appear to be in stark contradiction to the laws of our day-to-day world. In this way, particles of the nanocosmos can sometimes take on wave-like properties: an atom, which is apparently a "solid" entity, can pass through two small gaps at the same time, like a wave, subsequently emerging again whole on the other side.



Particles acquire completely new properties when their size approaches a nanometre. Metals become semiconductors or insulators. Some substances, such as cadmium telluride (CdTe), fluoresce in the nanocosmos in all the colours of the rainbow, while others convert light into electricity.

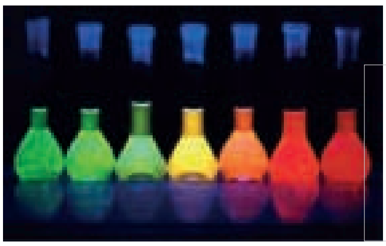
When particles become nanoscopically small, the proportion of atoms on the surface increases greatly in proportion to those inside. Surface atoms, however, frequently have different properties to those in the centre of the particle, and usually become much more ready and prone to react. Gold for instance becomes a good catalyst for fuel cells at nanoscopic sizes (see also Mobility). Nanoparticles can also be coated with other substances, allowing materials of such composite particles to combine several properties. One example: ceramic nanoparticles with organic shells, which reduce the surface tension of water, for the coating of non-misting bathroom mirrors.

Magnetite nanoparticles in oil. The fluid can be controlled and shaped magnetically.

Specially-coated nanoparticles of magnetite, an iron oxide, in oil create a ferro-fluid, a liquid that can be shaped magnetically. Ferro-fluids are being used in an increasing number of applications, such as sealing agents in rotary seals for vacuum containers and hard disk housings, or in adjustable vibration dampers for machines and cars.

Magnetotacticum bavaricum. Magnetic bacteria can synthesise chains of nano-magnetites and be used as a compass needle.

Yet nobody should be intimidated by the complexity of nanotechnology. Even an apple is complicated – cells, ribosomes, DNA – which has in no way impaired the popularity of this fruit.



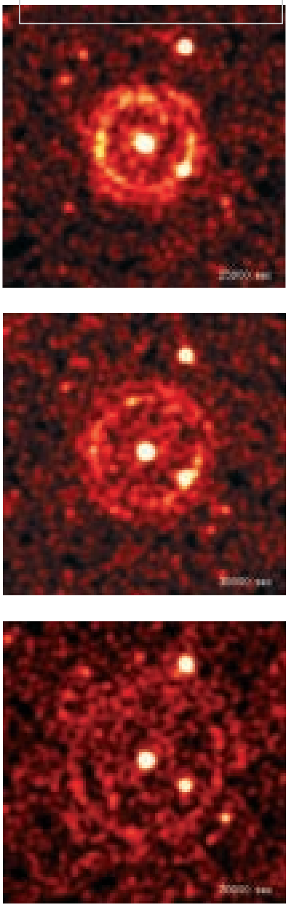
Cadmium-telluride particles fluoresce, the colour depending only on the particle size.

Instruments and processes

Eyes for the nano-cosmos

Nanotechnology in space: The reflectors of the European "Newton" x-ray telescope are polished to an average smoothness of 0.4 nanometres, enabling them to see sources of x-ray radiation in the Andromeda cloud

A scientific sensation: a flash of gamma radiation burns rings in a galactic dust cloud.



What does the European "Newton" x-ray telescope have to do with nanotechnology? It gathers the x-ray radiation from distant objects with 58 waste-paper basket-sized reflectors nestling inside each other like the layers of an onion and coated with gold vapour. The reflectors have an average surface unevenness of only 0.4 nanometres – a masterpiece of technology in which Carl Zeiss AG played a major part.

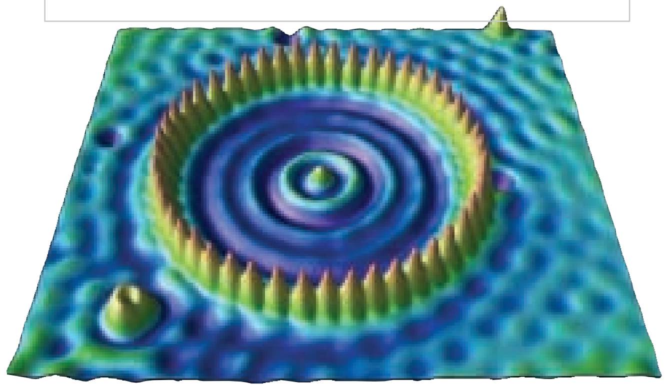
Precision x-ray reflectors for x-ray spectroscopy and microscopy are built up of several hundred layers of two different heavy elements. The demands placed on such reflectors are even more extreme, and the layers may only deviate from the ideal by fractions of the diameter of an atom. This technique is being mastered at the Fraunhofer Institute for Material and Beam Technology in Dresden.

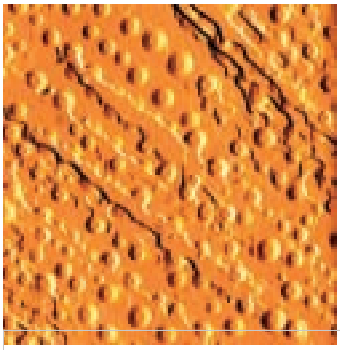
The trick of the layered reflector has also been discovered by nature for the spectrum of visible light: the nocturnal squid *Euprymna scolopes* directs the light from luminous batteries downward with tiny mirrors of reflectin proteins, imitating a patch of starry sky to any predators swimming below it. This example of biological nanotechnology was discovered recently at the University of Hawaii.

Scanning probes

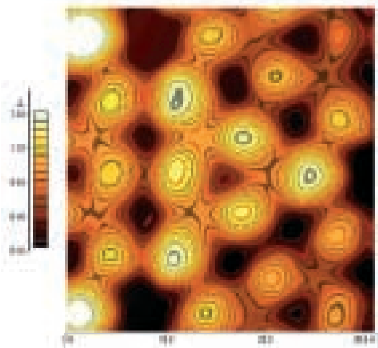
Scanning probes as the eyes for the nano-cosmos might appear less spectacular, although they ultimately won the Nobel Prize for the development of the father of all scanning probes, the scanning tunnel microscope. In scanning electron probes, piezo crystals guide a scanning head repeatedly and slightly

"Quantum Corral", by Don Eigler, IBM. The waves on the inside reflect the likelihood of encountering an electron.

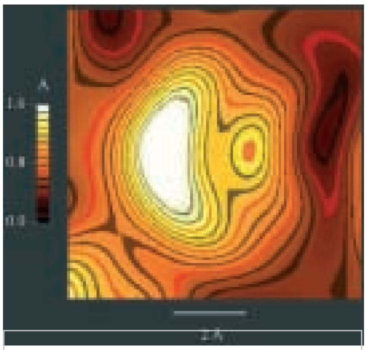




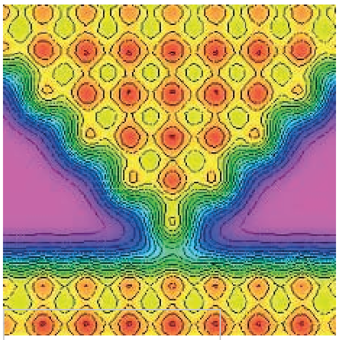
Potassium bromide crystal with atomic terraces. The salt on your breakfast egg looks similar.



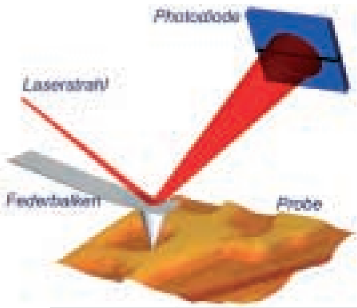
Silicon in close up, electron density contours under the scanning force microscope.



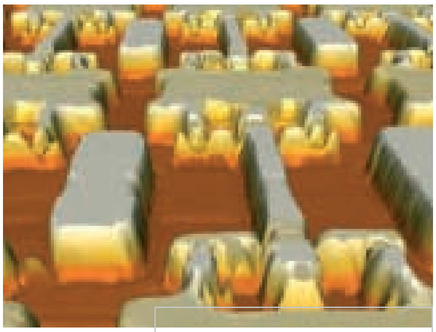
The foremost atom of the sensing head emits two electron clouds, orbiting just as described in the textbooks.



Schematic view of the classical tip of a scanning tunnel microscope.



The scanning force microscope: the deviation of the sensor needle is transmitted to a photocell by a laser beam.

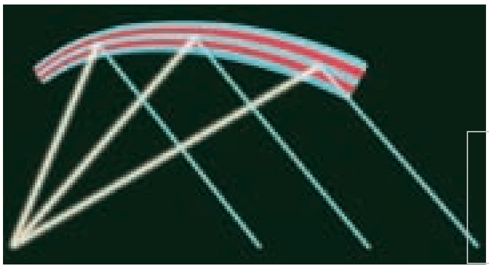


"Capacitive" probes can also be used to represent the switching processes on a chip.

offset over the subject of interest, such as the fields of atoms. The movements are minuscule, and the distance of the head from the atom field usually less than the diameter of the atom. In this region something happens: sometimes a current flows, sometimes minute magnetic fields are detected. Computers interpret the measurements graphically on a surface, creating an image, accurate down to the last atom, depending on the measurement principle.

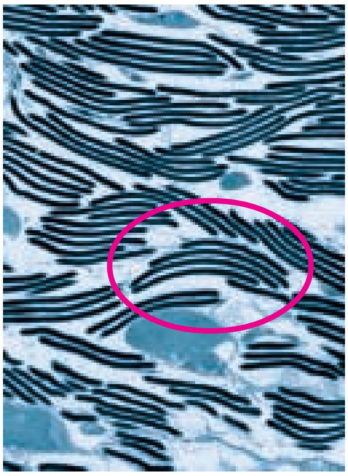
An especially subtle process is used by the scanning force microscope. This senses the minute forces exerted on the foremost atom of the sensing head by the atoms in the atomic field.

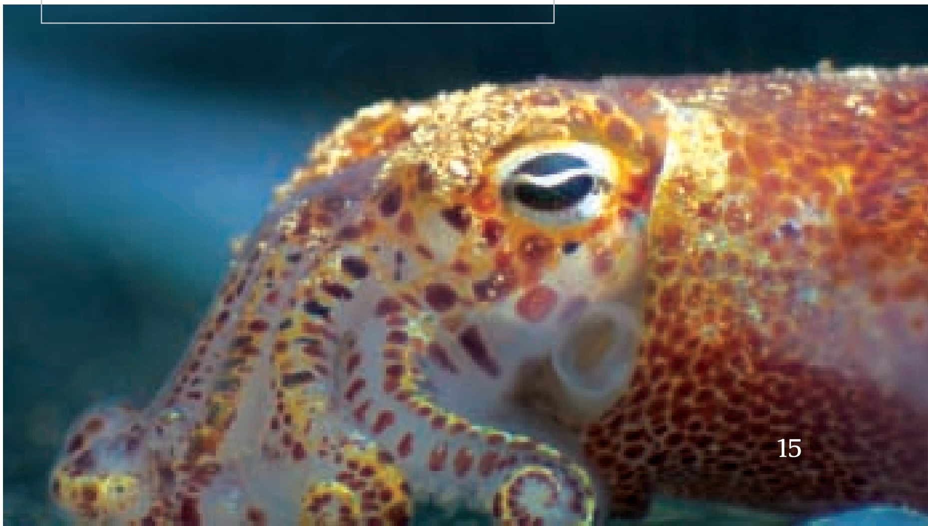
The process can even obtain a view into the electron shells of the atoms – revealing the secrets of the ultimate level of matter. The current world record for resolution is held by the University of Augsburg.



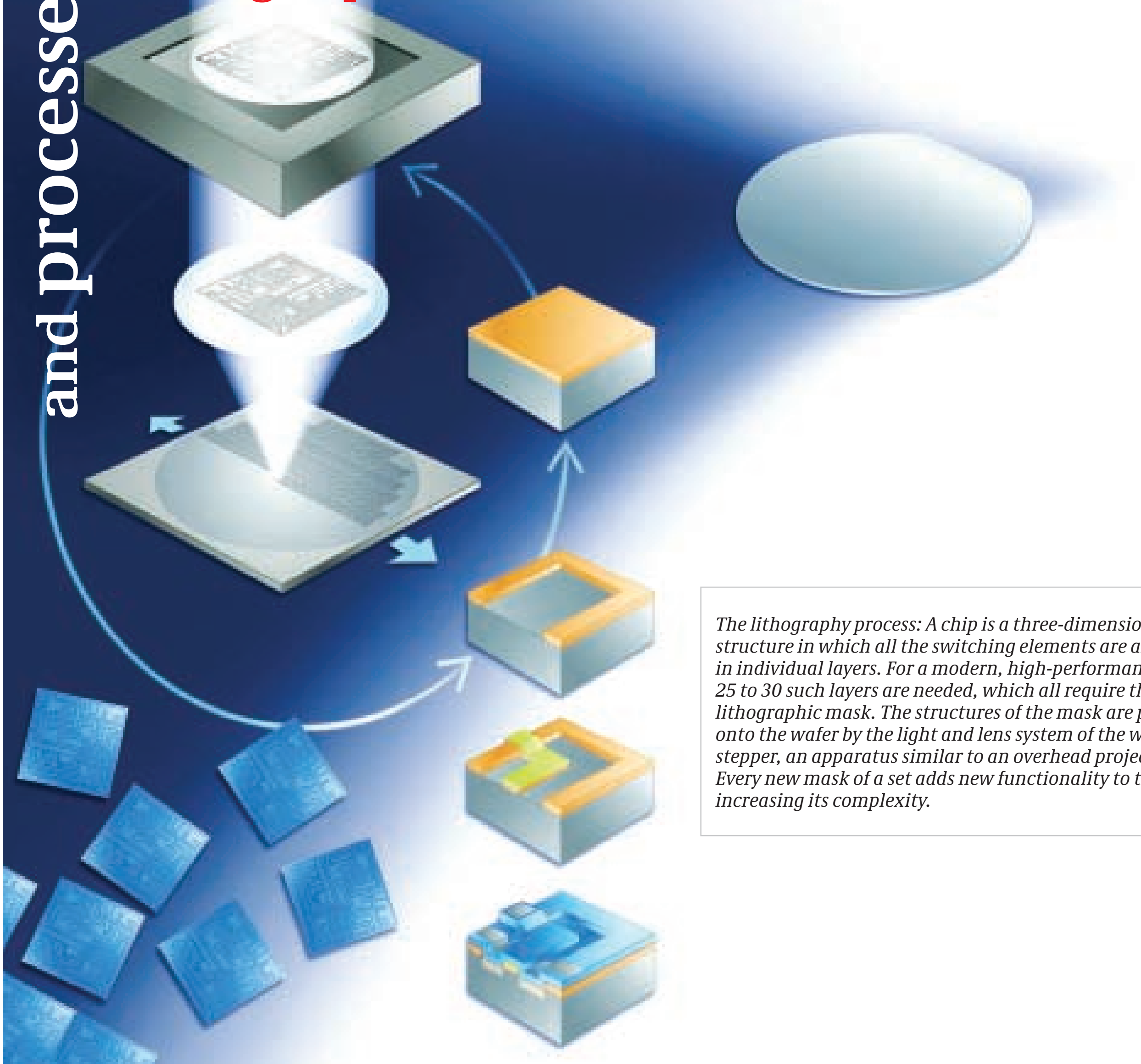
Curved multi-layer reflector for high-performance x-ray analysis.

„Euprymna scolope" confuses its enemies with multi-layer light reflectors of reflectin protein. The light is provided from luminous batteries.





Writing implements



The lithography process: A chip is a three-dimensional structure in which all the switching elements are arranged in individual layers. For a modern, high-performance chip, 25 to 30 such layers are needed, which all require their own lithographic mask. The structures of the mask are projected onto the wafer by the light and lens system of the wafer-stepper, an apparatus similar to an overhead projector. Every new mask of a set adds new functionality to the chip, increasing its complexity.

Lithography

In the world of computers, lithography stands for the technique of producing computer chips with the aid of light. In this process, the highly polished surface of a semiconductor material, a silicon wafer, is coated with a light-sensitive protective coating onto which the image of a circuit is projected. The development of the protective coating reveals the exposed (or unexposed) areas of the wafer, which are then given the required electrical properties by processes such as etching, implantation of foreign atoms and deposition. The repetition of the process with new patterns and circuits ultimately creates some of the most complex structures ever created by man: highly integrated circuits, or chips. Transistor densities have now increased to the point where a half a million or more transistors could fit within the dot made by a pencil.

Modern chips have structures which are even smaller than the wavelength of lithographic light: these use krypton-fluoride lasers with a wavelength of 193 nanometres in order to create structure widths of 130, and soon 90, nanometres, which is made possible with a range of ingenious optical tricks such as “optical proximity correction” and “phase-shifting”. The foundations are currently being laid for Extreme Ultra-Violet (EUV) lithography, which uses wavelengths of 13 nanometres, and which will ultimately be able to produce structures of only 35 nanometres in width in the silicon. The demands on the mask material are naturally tremendously exacting: a 10-cm long plate must only expand by a few tenths of a nanometre when warmed by one degree Celsius, i.e. by only a few atomic diameters. The required evenness of a few atomic diameters also lies at the limits of what is in principle feasible.

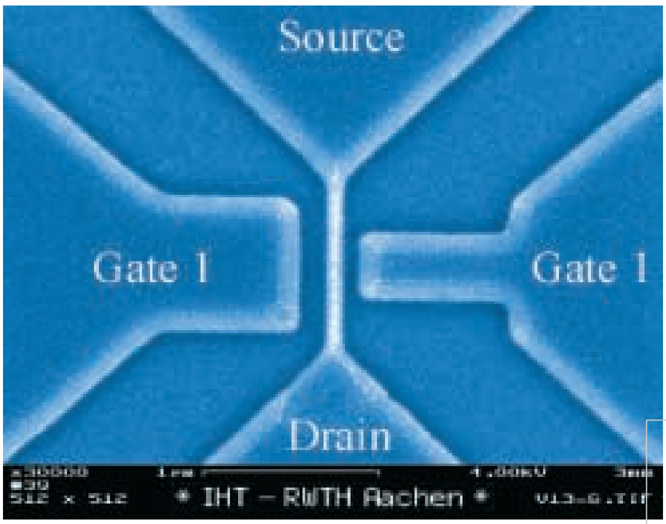
The rise of Dresden as an electronics location is a success story for German research support. Around 16 000 jobs have been created in the region, providing a great innovative effect throughout the German economy. In projects supported by the German ministry for research (BMBF), 44 partners from industry and state research institutes, including 21 medium-sized companies, have developed the standard for the future use of 300-millimetre diameter silicon crystal wafers for the production of highly complex integrated circuits. The Advanced Mask Technology Centre in Dresden, where the means of structuring future nanoelectronic chips are being developed, has a key role to play.

Prototype of an EUV wafer-stepper system for the production of future chip generations.

Nano-imprinting for medium-sized companies

Anyone who thinks of nanoelectronics probably has expensive facilities in mind that require investments of millions or billions of Euros but which nevertheless provide affordable products due to the shear volume of their output. There are however ways into the nano-cosmos available to medium-sized companies. These methods might look archaic at first glance; in the UV-nano-imprint process for example, the nano-structures are actually pressed mechanically into a coating covering the electronic carrier material, such as silicon. The template containing the delicate nano-structures is made of quartz glass, and quartz glass is transparent to UV light. When the stamp has been lowered into the paint, a UV light impulse causes the light-sensitive coating to polymerise, i.e. to harden. The template is then withdrawn, and the coating relief beneath is thinned. The silicon revealed can then be processed as required; by repeating the process many times with different templates, the complex structure of a chip is finally created, with transistors, circuits etc. Tiny structures of only 10 nanometres have already been achieved in laboratory trials. The process is not restricted to electronic components, and can also be used for the structuring of metals and plastics. The process could also lead to the creation of the lab-on-a-chip. The cost of a nano-imprint machine is currently estimated at less than one million euro, a fraction of that for similar equipment used in a modern conventional chip production factory. However, the UV nano-imprint technique will not necessarily provide cheaper products, since the throughput is much lower. For special mini-series – “mini” being measured in comparison with the large-series volumes of major processor producers - the UV nano-imprint technique could become the technology of choice.

Zerodur for lithography masks, this special ceramic remains stable even at nanoscopic sizes.



Imprinting the nano-cosmos: At the Institute for Semiconductor Electronics (IHT) of the RWTH Aachen, chip structure widths of 80 nanometres are already feasible with the aid of mechanical/optical methods. Applications: small-series, high-complexity circuits.

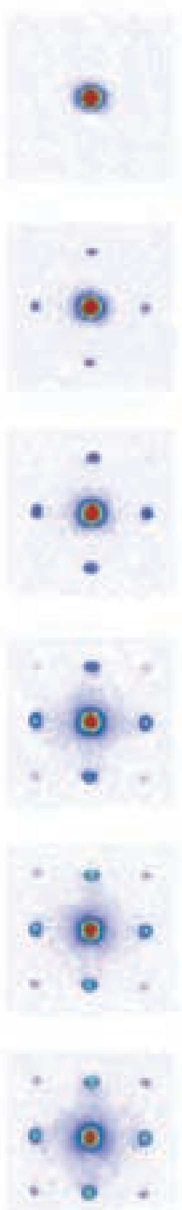
New impulses for science

Conventional spectrometer for x-ray structure analysis. Science owes much of its knowledge of the nano-cosmos to such instruments.

Underground racecourse for fast electrons

Quantum effects

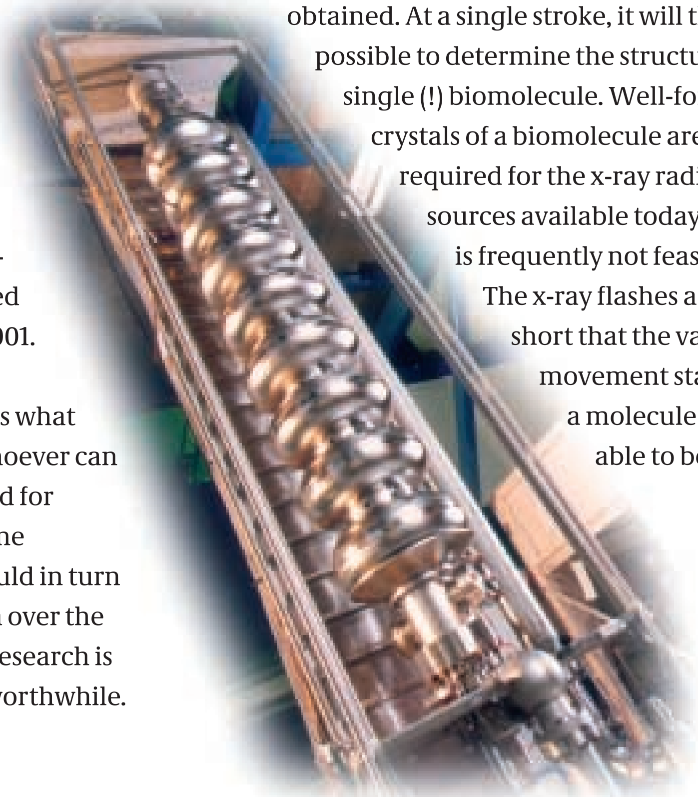
At the Ludwig-Maximilians University in Munich, matter is routinely being pushed to extremes of nanotechnology, under which it can sometimes reveal bizarre properties. For example, when vapour consisting of hundreds of thousands of rubidium atoms is cooled down to only one-millionth of a degree above absolute zero (-273°C) and forced together by a magnetic field, the atoms come together to form a “Bose-Einstein-condensate”, in which the atoms form a single unit, like a rank of marching soldiers. The quantum scientists at Munich can force such a block into a three-dimensional network of standing laser waves and manipulate it, e.g. by making the light traps so strong that the unit of the block breaks down into a “Mott-condensate”. This work was awarded with the nobel prize in physics in 2001. Why? Research of this type fills the quantum theory with life, and this is what has the say in the nano-cosmos. Whoever can fully understand and master it could for example develop more accurate time standards. More accurate clocks could in turn help to accelerate exchange of data over the Internet – this apparently esoteric research is therefore proving itself to be well worthwhile.



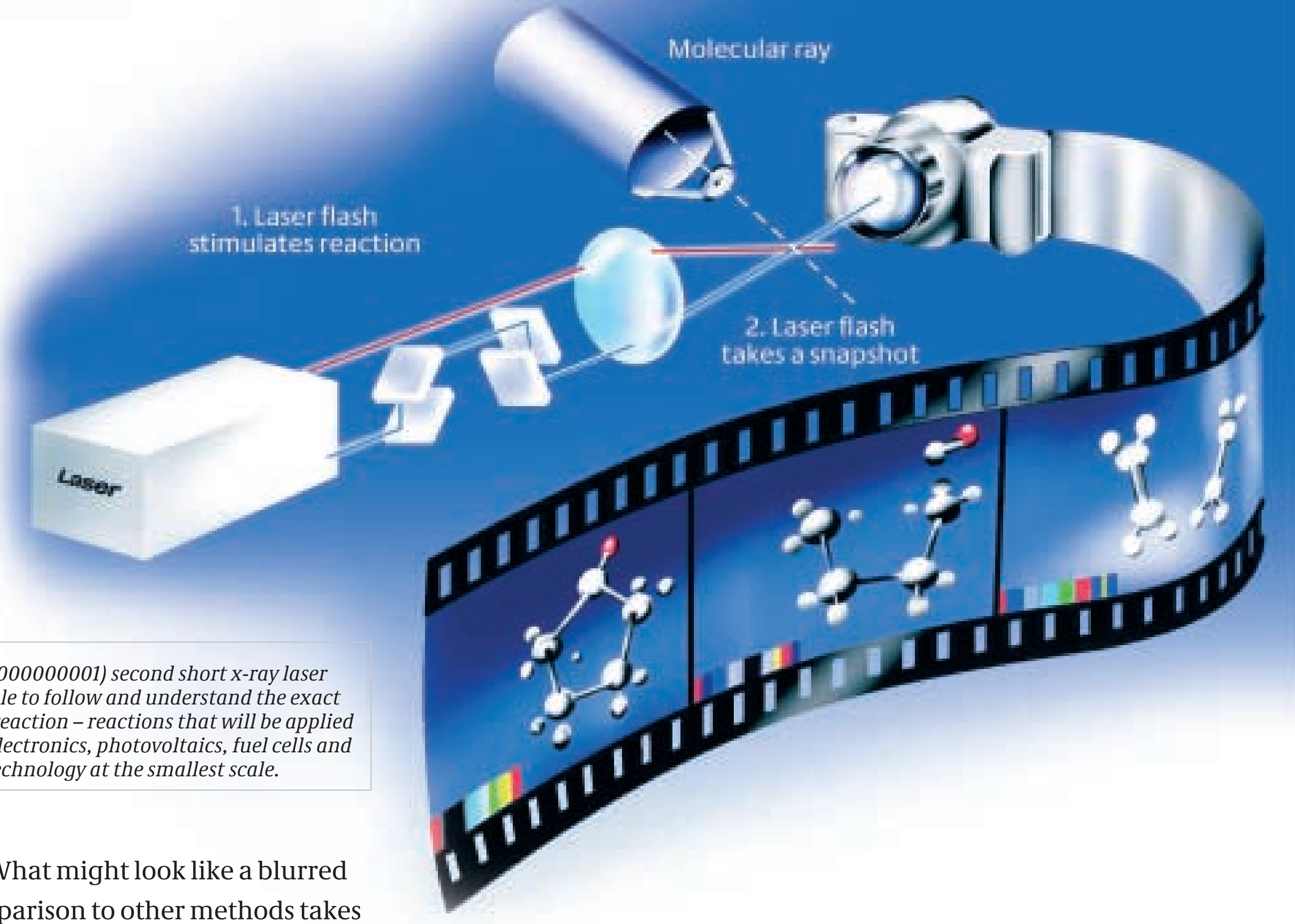
“Mott-condensate” – exotic matter for ultra-accurate time measurement

The XFEL x-ray laser – a leading light in nanotechnology

If everything goes according to plan, a few billion electrons are going to experience something very exciting in 2012. Starting on the DESY site in Hamburg-Bahrenfeld, they will be accelerated to very high energy by a superconducting electron accelerator, to be systematically diverted into swerving paths by magnets 3.3 kilometres further down the line. This will generate short-wave x-ray radiation of a very special sort: laser radiation. This radiation will be the most valuable that scientists have ever obtained. At a single stroke, it will thus be possible to determine the structure of a single (!) biomolecule. Well-formed crystals of a biomolecule are required for the x-ray radiation sources available today, which is frequently not feasible. The x-ray flashes are so short that the various movement stages of a molecule will be able to be



Superconductive elements for electron acceleration



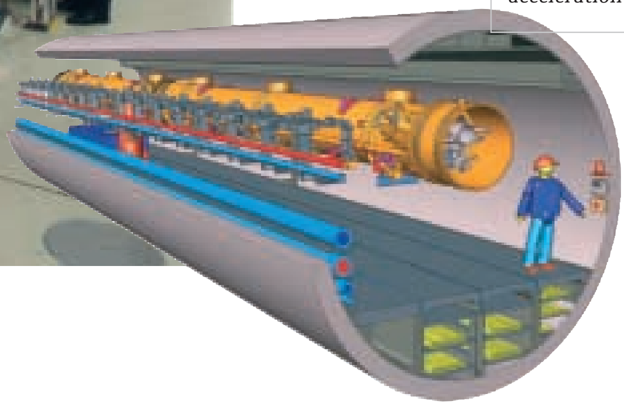
The femto (0.000000000000001) second short x-ray laser flashes make it possible to follow and understand the exact course of a chemical reaction – reactions that will be applied for example in opto-electronics, photovoltaics, fuel cells and solar cells and nanotechnology at the smallest scale.

properly filmed. What might look like a blurred whirlwind in comparison to other methods takes recognisable shape with the aid of the x-ray laser.

The secrets of friction can be decrypted. What creates friction, and how, will be determined by nanoscale groups of only a few hundred atoms.

The properties of individual clusters, agglomerations of a few hundred atoms, can also be better researched with the XFEL than with any other instrument. In short: science and technology will be given a powerful boost with Europe's greatest project in the field of nanotechnology. The planned overall costs of 684 million euro (as of 2003) will, in all probability, prove to have been more than worthwhile. Not just in terms of pure knowledge, but also in hard cash.

The free-electron laser under construction.

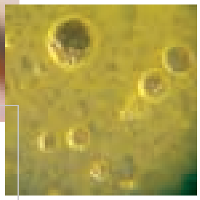


Graphic of the underground electron acceleration path

Material design on the nanoscale

Sol/gel processes for new materials

Sauce Béarnaise was created in honour of Henry IV, King of France, and was so called because he came from Béarn. This sauce represents a very good (and very tasty) example of a colloidal system. A colloid refers to a sub stance in which many fine particles are suspended in a stable condition in another substance.



Sol/gel for a King: Sauce Béarnaise, created in honour of Henry IV of France

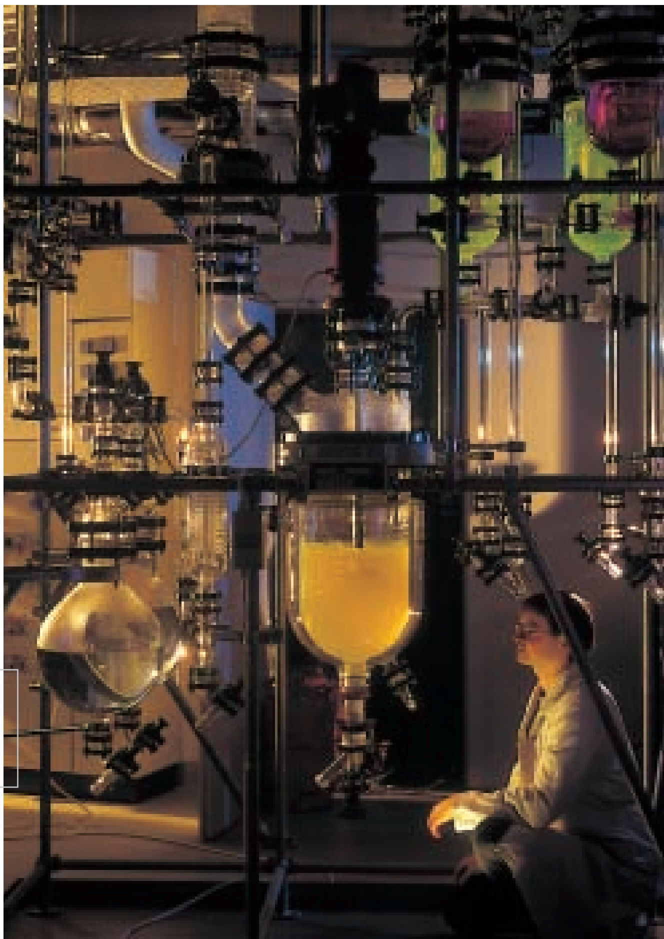
In the case of béarnaise sauce, these are droplets of vinegar suspended in melted butter. Creams and paints are further examples of colloids. With sol/gel technology, colloids also lead directly to the field of high technology.

In sol/gel technology, a (usually colloidal) sol is produced from soluble compounds such as those of silicon, in which droplets containing silicon are suspended in a carrier solution. When these are then sprayed onto a plate and heated, the carrier solution evaporates, and the silicon droplets gel to form a network. This gelled network then solidifies to form a hard ceramic layer. The plate is thus protected against corrosion and scratches.

Sol/gel technology comes in hundreds of variations for different materials. Gelled sols can also be formed into threads, which when fired are converted into ceramic fibres. Sols can also be used to produce nanoscale powders, which can be fired much more easily and at lower temperatures than conventional powders, and which can withstand the highest pressures and temperatures.

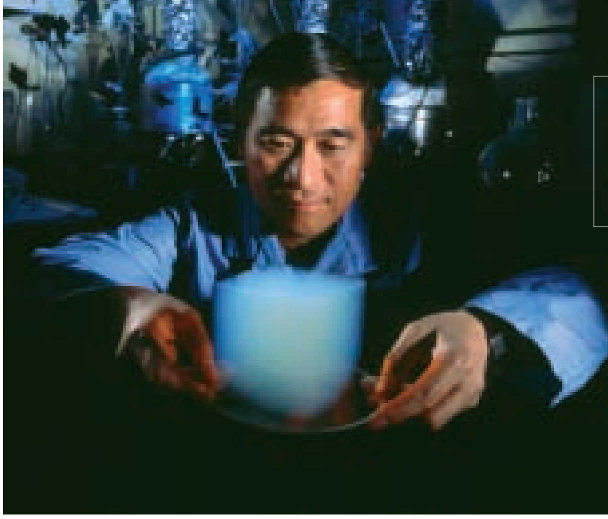
Sol/gel technology is also suitable for the manufacture of sophisticated optical components such as fibre-optic cables, frequency doublers, and micro-lens fields. This type of nanotechnology promises nothing less than a revolution in materials technology.

The gel solvent can also under certain circumstances be removed in such a way that the gel retains its original volume, producing a high-porosity material of very low density, an aerogel.



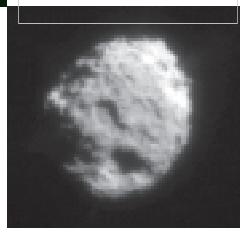
Fit for the finest particles: Sol/gel particle reactor

Double-glazing filled with an aerogel reduces heat losses.



Aerogel as a scientific dust-trap. Particles are securely trapped in a melted aerogel compound.

The comet "Wild 2" has been visited by an aerogel.



Aerogels

Aerogels are everyday objects, which have been used by bakers for a long time in the form of meringue. This is egg white, which is sugared, whipped up and baked. Anyone holding it in their hand will immediately feel how their fingers become warm. This is due to the fact that the air in the meringue is locked inside millions of microscopically small bubbles. It cannot therefore circulate or exchange heat, making the meringue an excellent heat insulator, just like polystyrene. Similarly constructed aerogels of foam glass also make first-class heat insulators.

Egg white is colourless, although meringue is white. This is due to the compartmentalisation of the whipped egg white into bubbles only micrometres in diameter. In such fine structures, light is refracted into all the colours of the rainbow, but the overall result is white. Nanometre-sized pores no longer refract the light. Foamed glass material with nanometre-sized pores is almost as clear and transparent as normal window glass. Double-glazing filled with such foam produces good window glass with outstanding heat insulation.

Because such foams consist almost exclusively of air, they are referred to as aerogels. The designation "gel" comes from the production process: a catalyst is added to the aqueous solution of a suitable material, which creates tiny, thin-walled cavities that join together to form chains, and then groups of chains, a gel, which on drying then becomes a feather-light aerogel.

The most travelled aerogel was that used in the CIDA dust-analyser of Hoerner & Sulger GmbH, which in January 2004, after a journey of five years and a distance of 3.22 billion kilometres, collected dust from the comet "Wild 2".

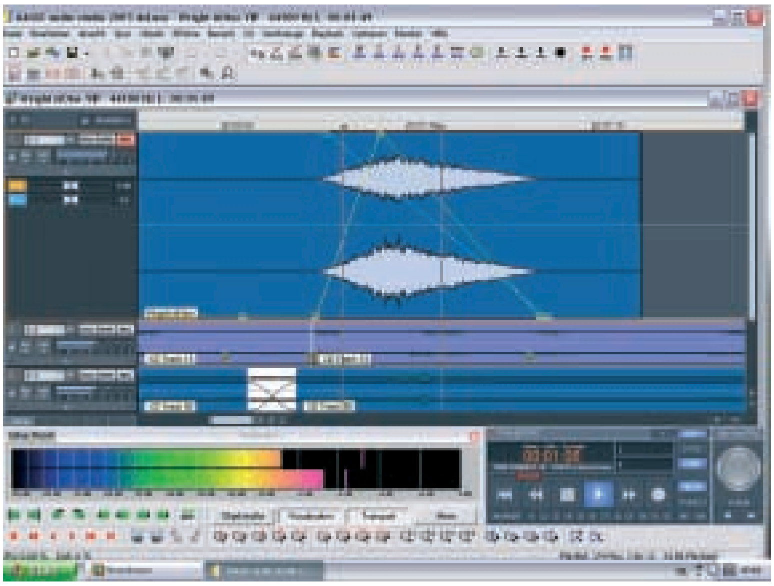
A material interspersed with a large number of bubbles has a large internal surface area. The greatest possible internal surface area, i.e. infinite, is that of the Menger sponge, thereby making its volume zero. The sponge exists only in the minds of mathematicians. The actual internal surface area of aerogels is however still large enough to produce some astounding effects. A sugar-cube-sized piece of aerogel made of carbon material may have an internal surface area of as much as 2 000 square metres. This and other properties ensure carbon aerogels have a secure place in the energy technology of the future. They can be used to construct condensers with a capacity of up to 2 500 farads as energy accumulators for peak power requirements, such as those in an electric car. This amazing foam will also enable the design of better lithium batteries, new types of fuel cells, etc. Seldom has anything of such little actual substance demonstrated such versatile potential.
How typical of nanotechnology!

The Menger sponge is used by mathematicians as a "universal curve". This is created when the procedure shown below is repeated infinitely.

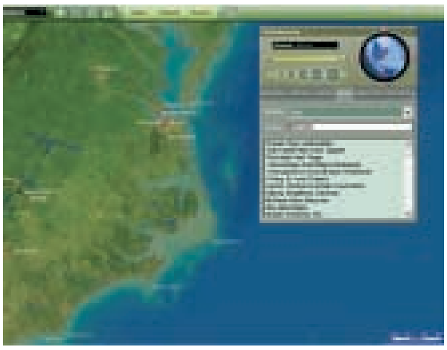
Nanotechnology in society

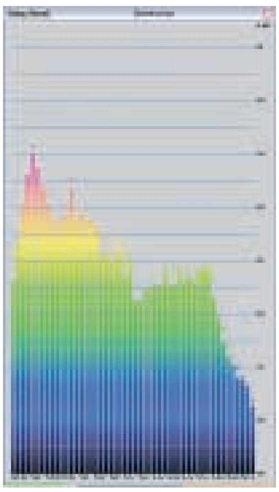
The networked world: Nanoelectronics

From the notebook in the studio to studios in the notebook – the status of the technology



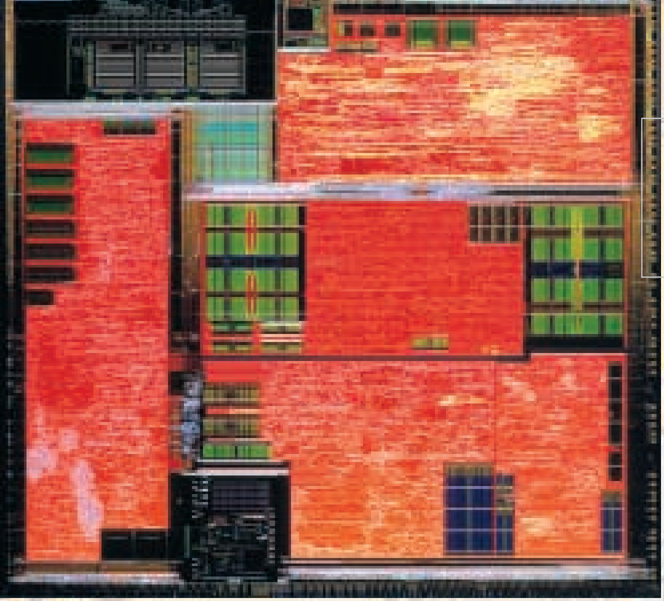
The task: Four-and-a-half minutes of radio about the first powered flight of the Wright brothers, accompanied by a little atmosphere. Armed with the notebook PC, what does a radio writer do, assuming that he takes pride in his job? First he takes a look at the place where it happened. The virtual globe shows Kittyhawk lying on a strip of land a few kilometres wide along the shores of the North Atlantic, bordered by the Kill Devil Hills, so the Wrights would have been able to hear the rumble of the breakers. That can be obtained from the sound archives, as well as the stiff breeze that was blowing for the first flight, as described by the *Encyclopaedia Britannica*, together with the rustling of the grass on the dunes. The engine turned at a speed of 1 200 rpm, and the sound archives provide a vintage Chrysler, which is droning nice and deeply. The spectrum analyser in the sound program shows plausible frequencies, all OK so far. The first flight lasted for twelve seconds, so a passage is selected in which the sound falls off at the end, because of the Doppler effect as the aircraft passes the microphone. Everything is put into the sound program and overlaid on different tracks. The aircraft flies from left to right, which can be set up with panorama curves. The engine noise rises and falls, adjustable with volume curves. And then Orville Wright is seen, flying very convincingly over the Kill Devil Hills in the Flyer One, just as on 17th December 1903, with the noise of the surf and the whistling of the dune grass – all on the notebook. (Other aviation pioneers, like the German Gustav Weisskopf, has already flown in 1901, although they were unable to make their inventions practical.)





Twenty years ago, this task would still have been unaffordable for a single person, and would also have needed tonnes of equipment: today, all that is needed is a notebook PC, a small desk and a few hours of time. The encyclopaedia has been put onto a DVD, which replaces the 30 heavy tomes and is much more convenient for a quick search than its paper counterpart. The sound program too comes in immaterial form on the hard disk, and from its many virtual racks offers an infinite range of effects. The development of the modern computer has set in motion a wave of dematerialisation, which will also result in a reduction in energy consumption. The price reduction in hardware and software has also placed amazing production facilities in the hands of creative people who no longer need huge resources.

In future, the library worn on the wrist will be nothing unusual, in the same way as interactive mobile communications.



A TV studio small enough to fit on the fingernail: Multimedia chip with controller for high-resolution display control, with the power consumption of a pocket torch.

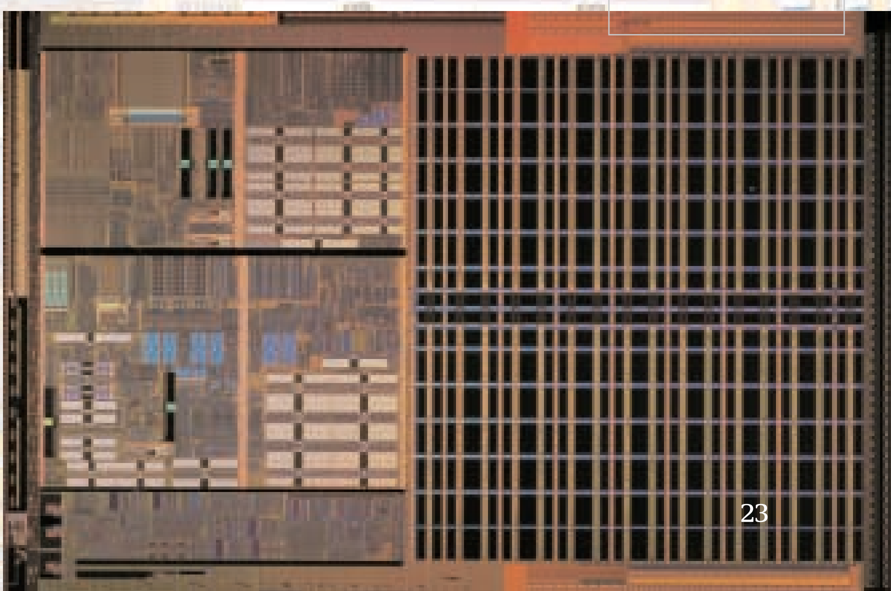
Go Nano! The coming years

The transistor technology used today in computer processors is called CMOS (Complementary Metal Oxide Semiconductor), and was developed, amongst other things, for the first electronic wristwatches, since it used much less power than its predecessors. Since the 1970s, experts have been forecasting again and again that the technology would reach its limits of development within 10 to 15 years, and are still doing so today. This time of course, the electronics industry has a compelling reason to anticipate a break with the tradition of the continuing miniaturisation of its components: on the way into the microcosm, the actual building blocks of matter, its atomic structure, is gradually becoming visible. The electronic shells of atoms are however the smallest components that can be joined together under normal conditions to form technical structures. A fundamental limit is therefore in sight. A conductor path cannot be any thinner than an atom.

CMOS technology has already long been subject to limits that sometimes seem very curious. The circuits connecting the transistors of a chip are already so fine that aluminium atoms would be unstable in such an application. They would simply be washed away by the electron flow like gravel in a stream: the specialist term for this phenomenon is "electro-migration". The answer: copper circuits, which are even better conductors, thereby speeding up the flow of signals on a chip. The circuits have now also been pushed so close together that this creates a detectable capacity, as in a capacitor. If this effect were not taken into account in chip design, the chip could get out of sync.

Certain components of chip transistors are gradually being reduced to a size of less than 20 nanometres. This comes into the realm of quantum theory, where the tunnel effect starts to come into play: currents start to flow in larger transistors where there should be no current – the electronic gateway system springs leaks. Although the currents are tiny, with millions of transistors they add up to considerable losses, and the processor becomes hot. These uncontrolled charges also cause logic errors, which can be fatal.

In the case of very fine structures, the wave characteristics of the electron ultimately start to become visible – as described by quantum theory. Many scientists however see this situation as an opportunity to develop a completely new type of electronics, which could produce a quantum computer that could open up a totally new mathematical universe.

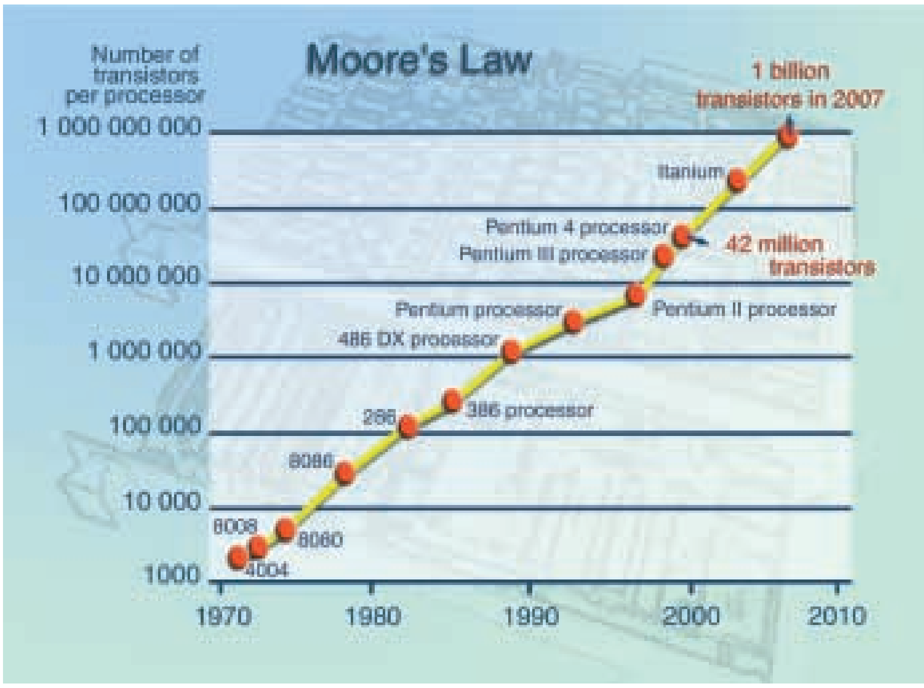


64-bit processor from AMD for PC applications with 106 million transistors using 130-nm technology.

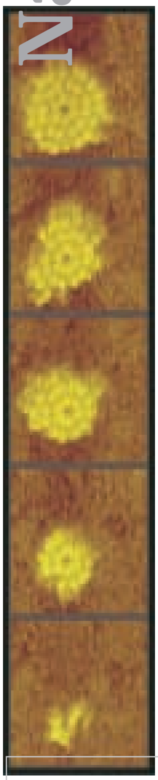
The networked world: Nanoelectronics

Moore's law reaches its limit

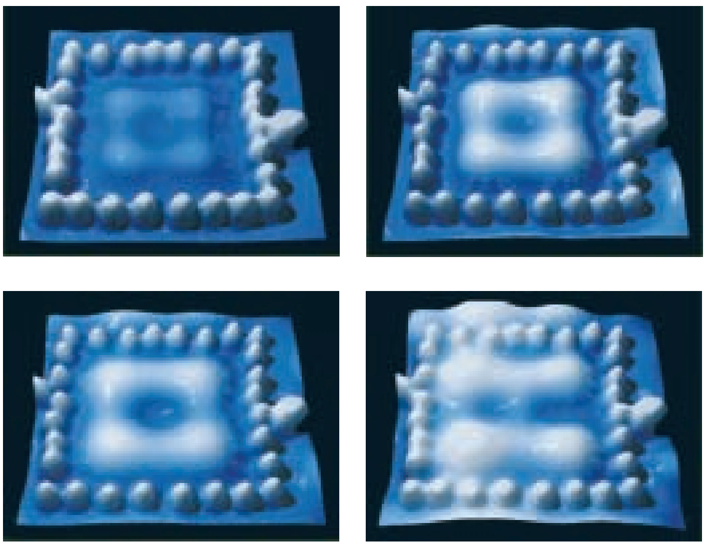
As early as 1965, Gordon Moore, co-founder of the firm of Intel, realised that the capacity of microchips was doubling about every 18 months. This "law" is now also being brought into question by a very human problem. While approximately 50 percent annual growth in the number of transistors on a chip is being achieved, analysts complain that chip design productivity has only increased by 20 percent per year. The industry has attempted to counteract this trend by continually increasing the size of design teams: now consisting of from 250 to 300 people, these have attained a head-count that is simply no longer manageable.



Unlimited growth is contradictory to Moore's Second Law, which states that the reduction in the size of structures and an increase of the price of the production plant go hand in hand. Until these limitations seriously limit further development, nanotechnology will continue to play an important role in the area of nanoelectronics. In fact, current CPUs are already fabricated with structures of under 100nm and containing more than 100 million transistors. If one believes the Roadmap for the Semiconductor Industry, whose forecasts are mostly based upon realistic technical developments, we expect to realize 45nm structures within a few years (2010), implying more than one billion transistors per chip. This will open up possibilities that we can only dream of today.



A tiny island of silicon on a silicon crystal gradually dissolves at 450 degrees. The knowledge of such processes is important for the quality of thin layers.

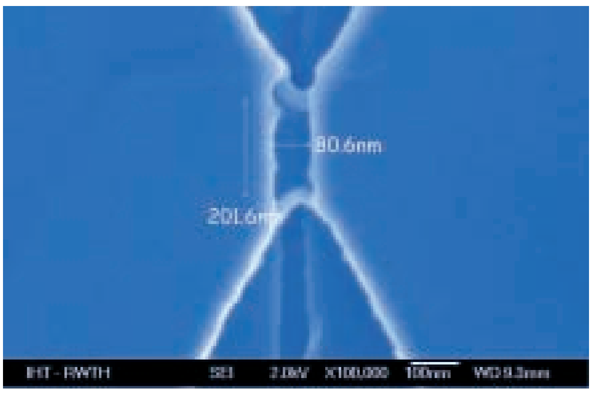


Manganese atoms on silver at the Christian-Albrechts University of Kiel. The electrons enclosed by the cage of manganese atoms form distribution patterns, which depend on the electrical voltage applied. Effects such as this will be important for the electronics of tomorrow.

Phase Change RAM

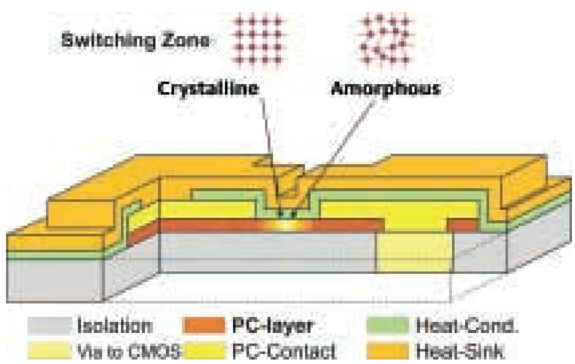
Today's data storage devices are based on various technologies that have their respective advantages and disadvantages. While magneto-mechanical hard disk drives (used typically in today's desktop computers) have a very high memory density and store data without the need for a constant source of electrical current, they are very slow in terms of data access. In contrast, DRAM (Dynamic Random Access Memory) is quick but the data needs to be constantly "refreshed" using pulses of electrical current. Flash Memory, which is found, for example, in MP3 players, mobile telephones and digital cameras, retain data without a constant supply of current but are not as fast as DRAMs and can only be used approximately 1 million times. Future nanotechnological storage concepts, which should combine the above-mentioned advantages: high memory density, speed, data retention without current supply and a long life-span, are from today's viewpoint MRAM (Magnetic Random Access Memory) and, as described in the following, Phase Change RAM.

Solid substances can occur in two extreme conditions: the crystalline state, in which the atoms are neatly arranged in a regular structure; or the amorphous state, in which the atoms are arranged irregularly. Common amorphous solids include types of glass including, for example, quartz glass. The same substance, silicon dioxide, can be found in its crystalline form in the mineral trade, where it is known as rock crystal. Crystalline – amorphous, a great deal more will be heard of these two material conditions in future, because they will probably determine the mass memory of the future. Some solids allow themselves to be changed more or less willingly from the amorphous to the crystalline state and vice versa; this phase change, which is generally achieved by the effects of heat, has found wide application in optical storage media. For instance, when a rewritable DVD is written, a special coating on the DVD changes its phase locally from "crystalline" to "amorphous" by means of the heat shock of a laser impulse, thereby also changing its reflection properties, so that a readable bit pattern can be written. Longer and stronger laser exposure makes the amorphous areas crystalline again, so that the DVD can be rewritten.



Phase-change materials in all probability now have a long career ahead of them in electronic memory systems, or phase-change RAM. In this case the phase change will not be carried out optically, but electronically. Short current impulses make the material amorphous with a high electrical resistance, longer impulses make it crystalline again with low resistance. The resistance of the memory elements is queried in order to read the information.

With phase-change RAM, it should be possible to achieve storage densities that enable a terabit to be stored on an area the size of a postage stamp – ten hours of uncompressed video with the finest quality. Notebooks with this technology would simply start up again where their owner left off – booting-up would no longer be necessary.



Right: PC layers for bit storage can be switched to and fro between the amorphous and crystalline state with current and heat impulses of different lengths. This patented design by the IHT of RWTH Aachen makes possible fast memory coupled with low power consumption.

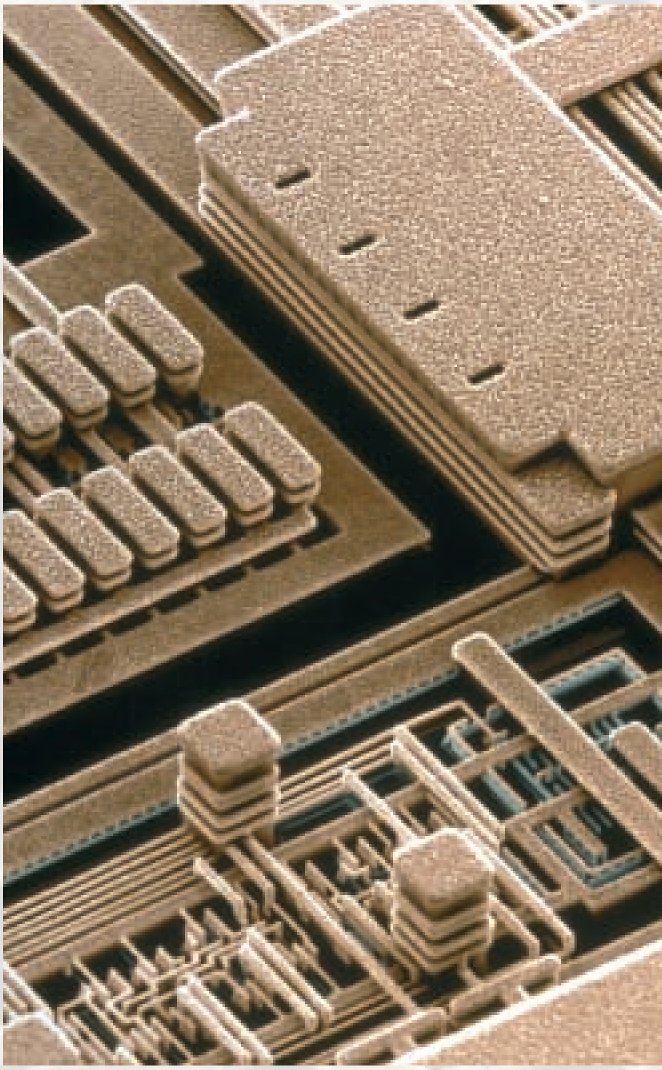
Left: Actual design of a phase-change RAM component

The networked world: Nanoelectronics

On with 3D – Chips are growing in height

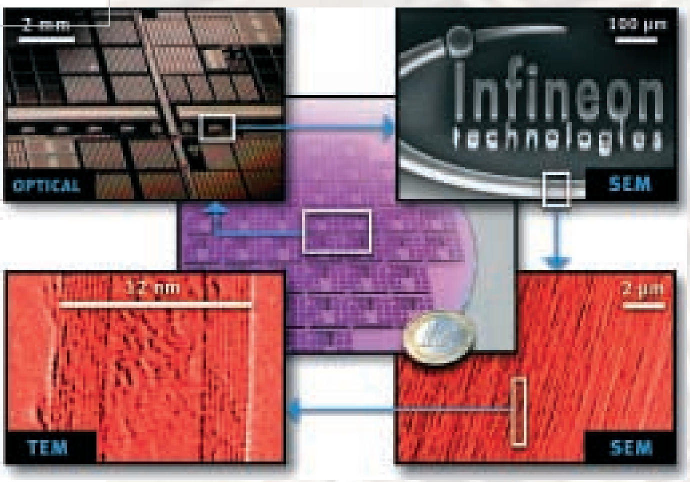
Skyscrapers were the economic solution of choice on the scarce property market of Manhattan when the need was to create new office and residential space. Chip designers had naturally also thought of the third dimension at an early stage, although the efforts came to nothing due to a whole range of problems.

A way could now have been found into this third dimension by Infineon AG of Munich, which has succeeded in growing carbon nanotubes (CNTs) on wafers – polished silicon plates on which the computer chips are installed. The Carbon nanotubes are first-class conductors, and therefore produce little waste heat, and can also be used as connections (VIAs) – that can also handle mechanical stress – between the different wiring levels of a chip. In the long term, Infineon researchers consider it possible to develop a genuine 3D technology for chips with the aid of CNTs, especially since CNTs, as excellent heat conductors, could also dissipate heat from the inside of 3D chips.

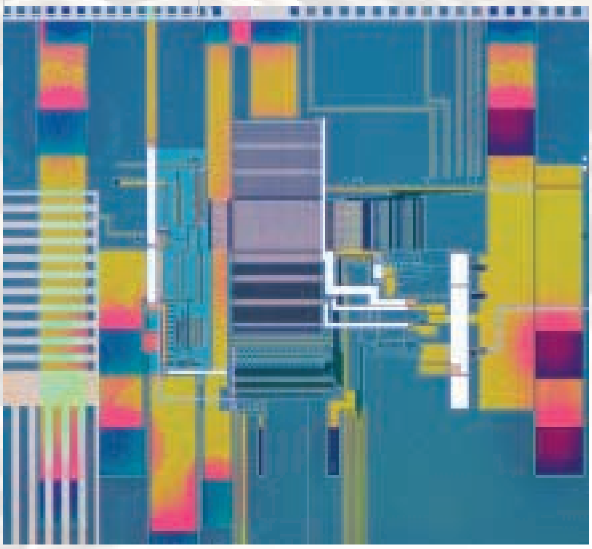


10 µ m

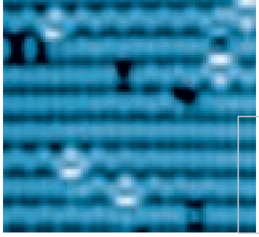
Specific growth of carbon nanotubes at pre-defined points of a silicon wafer by means of a microelectronics-compatible process.



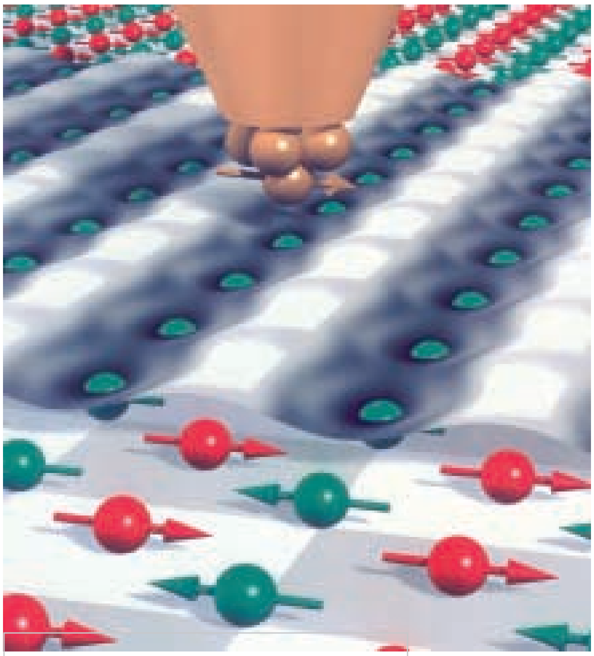
Modern art: Experimental structures for spintronic RAM



As complex as a miniature city – etched copper circuits of a chip (IBM), viewed with the aid of a scanning electron microscope. Modern chips have up to nine circuit levels.

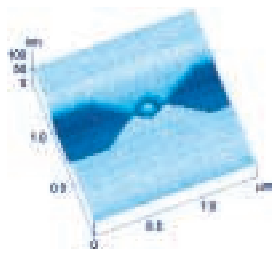


Individual organic molecules on silicon. Scanning tunnel microscope image, Ruhr University of Bochum.

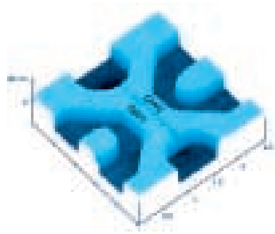


The magnetic probe of a spin-polarised scanning tunnel microscope scans the magnetic properties of individual atoms.

Finger exercises for the quantum computer: "Aharonov-Bohm interferometer", created at the Ruhr University of Bochum with a scanning force microscope.



Tunnel-coupled quantum wires – electrons travel through passages that would be blocked according to classical theory. Nanotechnology experiments are beginning to overtake the theory.



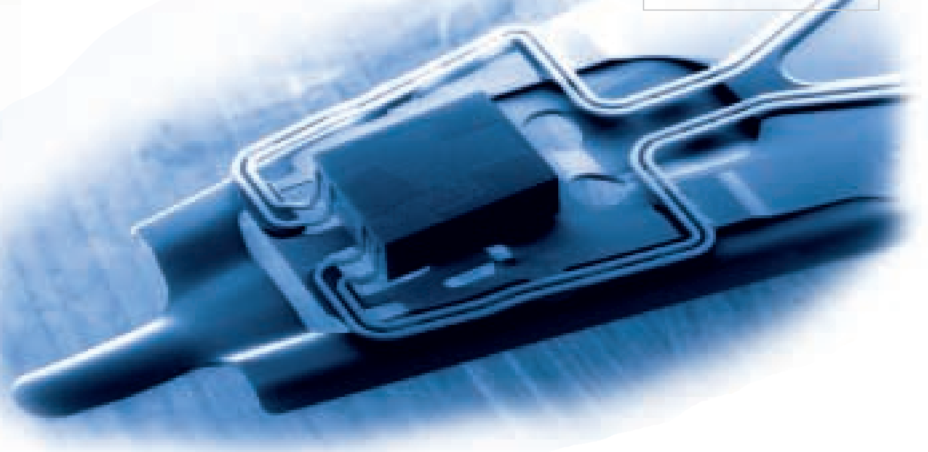
Spintronics – Computing with spinning electrons

A genuine revolution, which could carry Moore's law on well into the future, could be initiated by spintronic components, which in addition to the electrical properties of the electron also make use of their magnetic characteristics, their spin. The electron spin manifests itself as minute magnetic inertia, which reacts in a complex way with other magnetic conditions, and can therefore be used for electronic functions. One application of "spintronics" or magneto-electronics has already found its way into everyday use: new hard disks have "spin valve" thin-layer reading heads, which on the basis of the huge magnetic resistance discover very small magnetic domains, thereby enabling very high storage densities.

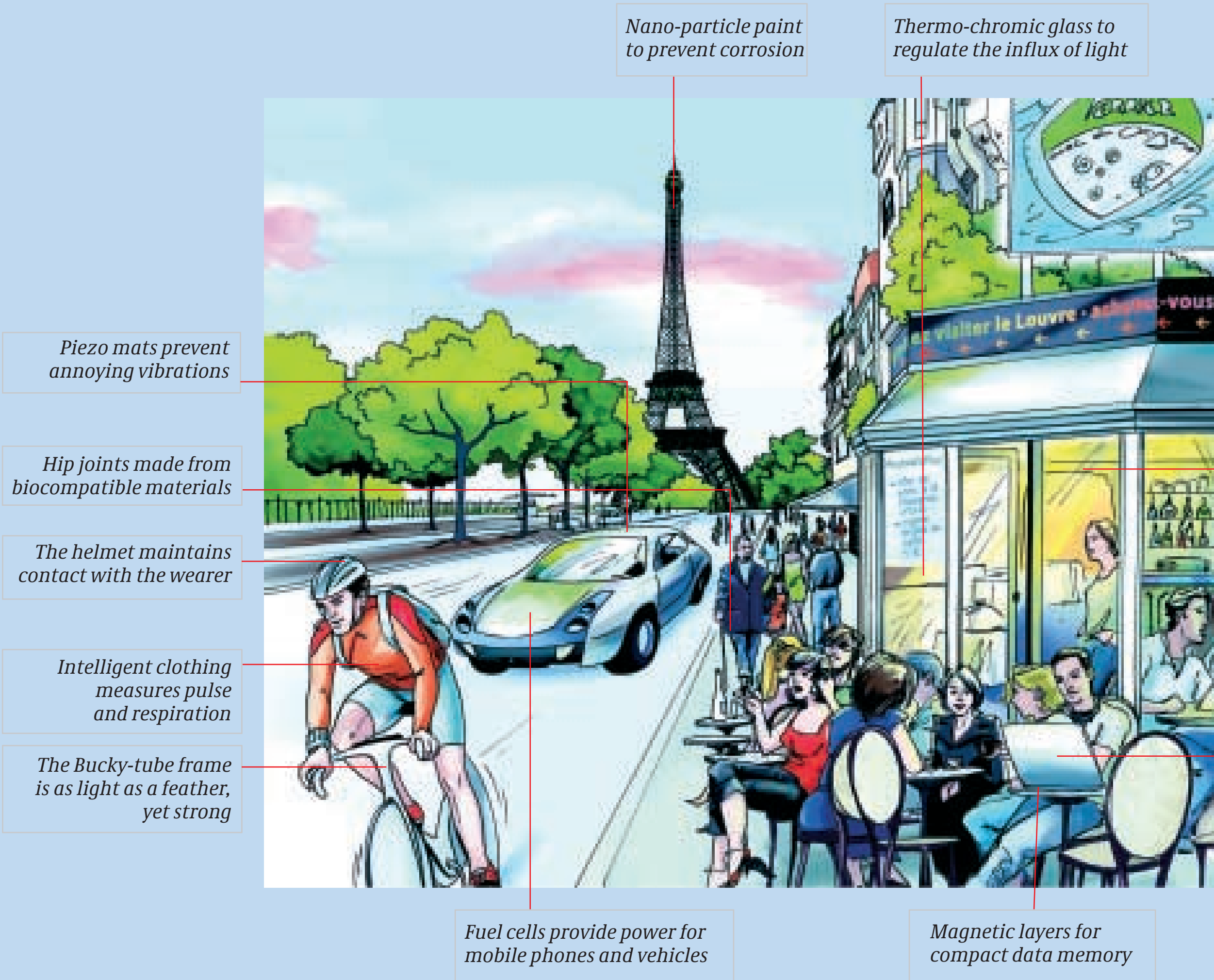
In MRAMs, magnetic memory chips, the information is stored in the spin of the magnetic layers. This development is of great interest for non-volatile main memory, and could in the long term lead to the replacement of mechanically-operated hard disks.

"Spintronics" is also being considered as the technology for a quantum computer at places such as the University of Würzburg.

New effects for powerful hard disks: the reader head uses the enormous magnetic resistance, with a semiconductor element of over 20 nanoscale layers.



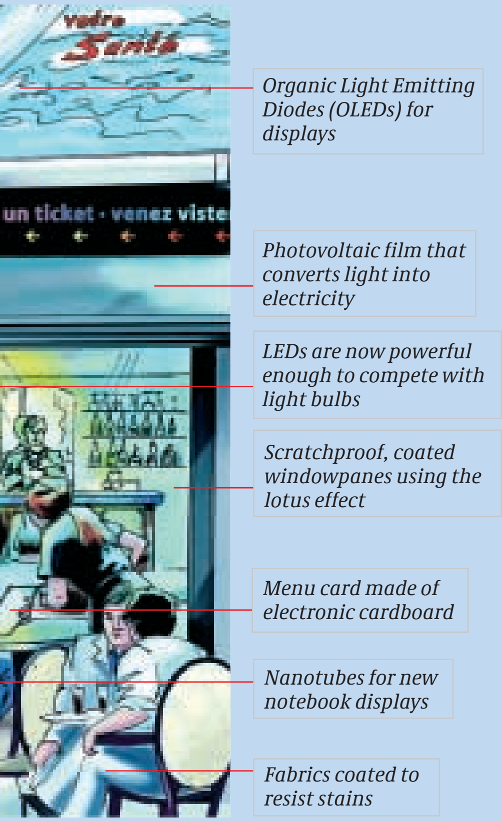
Nanotechnology in future everyday life



If nanotechnology becomes a part of everyday life, nothing would have to change dramatically on the outside. People will still like to sit at a street café, perhaps even more so that now, for the droning of internal combustion engines has been replaced by a discreet buzzing and swishing, like that made by the bulkhead doors on the Starship Enterprise. The stink of burnt petrol has given way to an occasional, hardly noticeable whiff of methanol used to power fuel cells. The service will be very quick: typing the order into the electronic menu has even automated the kitchen. The bill will be paid simply by pressing a cash card against the euro symbol printed on the corner of the menu. Tips will still be given in cash, because it clinks so nicely, although it will be hygienically coated with antibacterial nanoparticles. The windows of the café have become very expensive, because they provide so many functions – which ultimately makes them cheap again: they are resistant to dirt and scratches, they darken automatically when it becomes too bright, convert light into electricity, and light up as a huge display when required: it is fun to sit in the café or in front of it with other people to watch the World Championships.

Mature nanoelectronics offers the prospect of devices of captivating elegance, such as a genuine PDA (Personal Digital Assistant) in credit-card format (not that it couldn't be made smaller, of course, but because human hands still need something large enough to hold).

The object could be a matt black monolith without recognisable structures, the black surface gathers sunlight and converts it into electricity; it would be scratchproof and covered with a wafer-thin diamond layer, and under that a thin piezo-ceramic layer that converts sound into electricity and vice versa, in order to enable voice



communication. Naturally, it would also be capable of data transfer by light and radio.

The object could also see by means of a flat lens and a high-resolution image converter chip, would light up as a display on request, and would thus be a tape recorder, camera, video recorder, TV, mobile phone, and, via the European Galileo positioning system, an orientation aid all in one, and would on request read, translate and explain the menu in a Paris café, give the order in friendly, colloquial French, and then pay the bill.

It would also be able to recognise the voice and fingerprints of those allowed to use it, thereby protecting itself against misuse.

Nanoparticles in nano-solutions fluoresce in UV light, but are otherwise completely invisible. Finely distributed in fluids, they can be applied with inkjet printing technology, without changing the design or function of the marked object. Nano-pigments are therefore ideal for use in forgery protection.

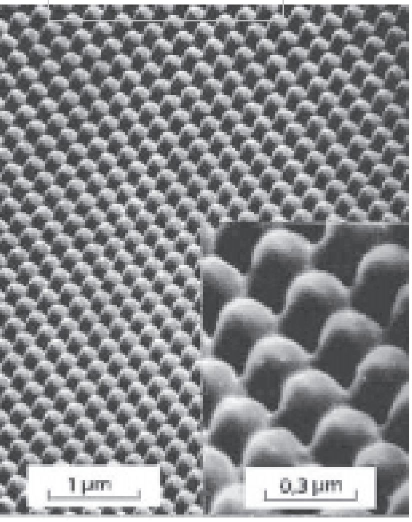
"Photo-chromic glass": the transparency of such types of glass is electronically controllable – for the office climate conditioning of tomorrow.

The virtual keyboard: touching a projected key is recognised by the system and interpreted as a press of the key.

As in other machines, nanotechnology will also replace quantity with quality in the car. The benefit of technology is that you can get by with less material, because the technology is reconciled with nature.

Nanotechnology in the car

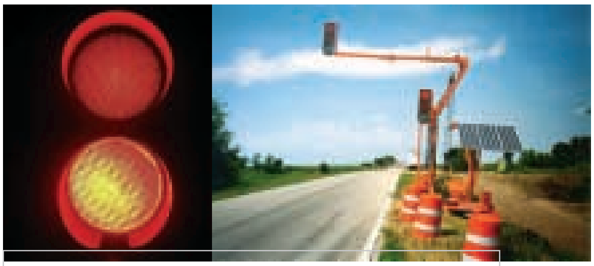
Small structures for the bigger picture. With the aid of regular, microscopic surface structures, distracting light reflections on displays and windows in the car can be prevented. The analogy provided by nature is the eye of the moth, which at night needs to see as much as possible, without being seen itself.



Windscreens can be made scratch-proof with coatings produced using sol/gel techniques, which contain hard, nanoscale particles – and still remain completely transparent, because nanoparticles are so small that they do not scatter the light. The principle already works for glasses, even though not yet fully perfected. The car finish could be provided with a lotus leaf structure that makes dirt simply run off.

Windscreens with nanoparticle coatings could also help in climate conditioning for cars by reflecting light and heat radiation, either to a greater or lesser extent, under electronic control. When applied to offices, such technology would help to save huge amounts of energy.

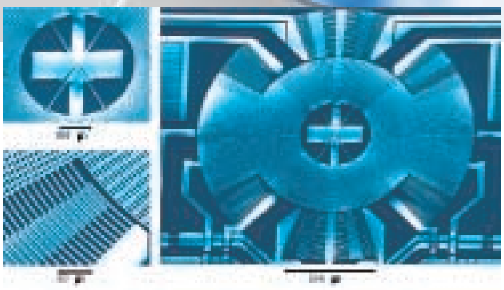
The lighting needed by a car is today already generated with a generous helping of nanotechnology: like all LEDs, the light-emitting diodes of quality brake lights have sophisticated, nanometre-size coating systems that convert electricity into light very efficiently. Another plus: LEDs convert electricity into light visible to humans almost immediately, while conventional brake lights fitted with bulbs need a little longer. The difference can mean several metres of braking distance. The luminosity of LEDs is now so great that groups of them can now provide dimmed daytime lighting for headlights.



LEDs in traffic lights save service time and energy. The amortisation time is no more than a year.

Current electronic safety systems such as antilock braking systems (ABS) or electronic stability program (ESP) come into action in critical driving situations; future systems will be able to avoid dangers automatically.

Injection nozzle for diesel vehicles. Future systems will be equipped with diamond-like wear protection layers only a few tens of nanometres thick.



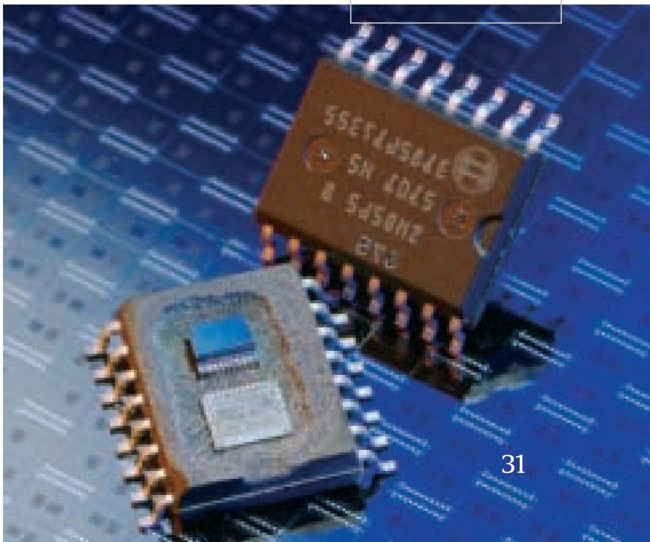
Balance organs of silicon: rotation rate sensor for vehicle stabilisation

White LEDs are now so powerful that they can be used in future as the light sources for headlights.

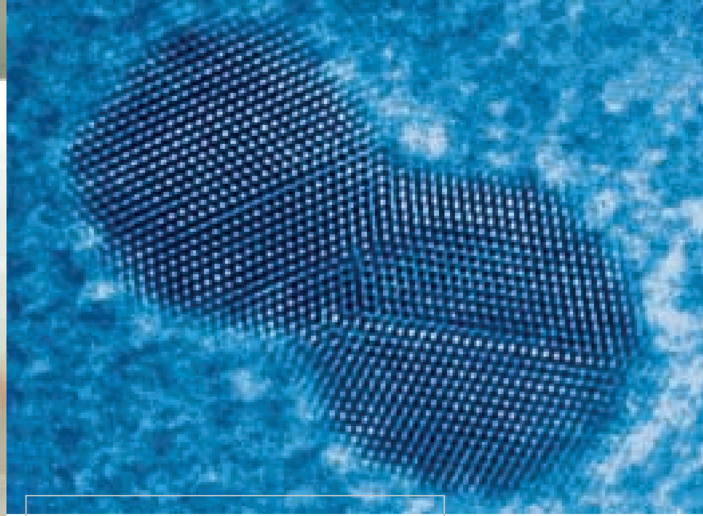
Paint finishes could also be designed nanotechnologically as a solar cell (an option that has not yet been developed). This power could be used to recharge the battery when the vehicle is parked – a feature that is already available using conventional solar cells – or to keep the interior cool using a heat extraction pump. The pump could in turn consist of a semiconducting, nanotechnology layer system without any moving parts. If the reverse is done, and the substantial waste heat from an internal combustion engine fed via such a semiconductor, it can be converted back into electricity – see also “Thermoelectrics” under “Energy and the environment”.

Fuel cells (see p. 33) will turn cars into a totally pollution-free means of transport. If the hydrogen fuel is also obtained from renewable energy sources, this source of power will be extremely environmentally friendly.

Electronics for vehicle safety: Acceleration sensor for a front airbag



Nanoscale perfume capsules give leather the right feel.



Nanoparticles of gold for new catalysts

Gold catalysts

Nanotechnology can also help gold on a new career path. While "plain" gold comes far behind platinum as a catalyst, gold nanoparticles on a porous carrier material provide a practical catalyst for cars that even during a cold start breaks down nitrous oxides and carbon monoxide into harmless substances. Gold nanoparticles are also promising new catalyst candidates for fuel cells.

All these advances will naturally also benefit other means of transport that have nothing to do with cars. Bicycles for instance would benefit from nanotechnology, especially with fuel cells and solar cells, creating an "eternal motion" machine that could travel across the country powered only by light, air and water, all light as a feather thanks to its carbon nano-fibre frame, LED lights and more.

Gold for the prevention of odours

Gold nanoparticle catalysts are currently also being tested as odour-preventers. In small air-conditioning systems such as those in cars, they can prevent smells created by bacteria in the system. In Japan they are already in service in toilets.

Nanotechnology in the service station

Car drivers can already come across micro-system technology in motorway service stations. The urinal bowls of advanced toilets are equipped with sensors, which signal any temperature increased to the associated electronics, initiating a flush. The electrical power required is supplied by a mini water turbine operated by the flushing process. Unlike systems with infrared sensors, the system cannot be put out of action by a piece of chewing gum.

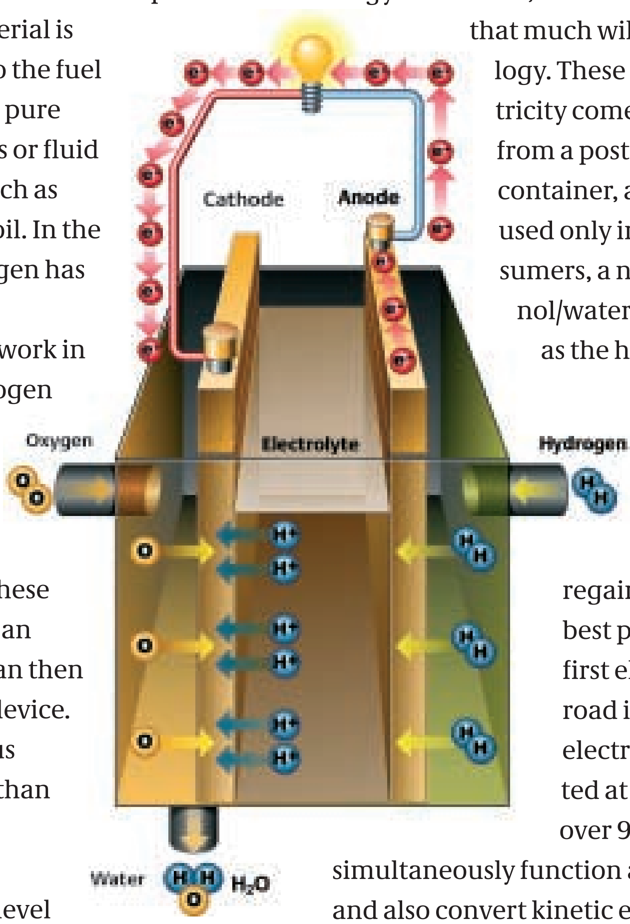
Nanotechnology urinals on the other hand work in a much simpler yet more sophisticated way: Thanks to the lotus effect on the bowl wall, fluid runs off easily, percolates through an odour-preventing fluid layer and disappears without leaving any traces behind – how true this is remains to be shown in practice. This technology is naturally also suitable for private households.

Service area urinal with vandal-proof micro-system technology. Nano-scale "lotus effect" coatings will also further simplify maintenance and cleaning.

Thanks to their nano-porosity, metallic “nano-cubes” from BASF can store large quantities of hydrogen.

Fuel cells – a device with a thousand uses

Fuel cells are similar to batteries: they supply electricity. However, while the chemical ingredients of a battery will be used up sooner or later, energy-rich material is continually resupplied to the fuel cell. This material can be pure hydrogen, or another gas or fluid containing hydrogen, such as natural gas or rapeseed oil. In the last two cases, the hydrogen has to be separated out in a “reformer” before it can work in the fuel cell. When hydrogen and oxygen combine, electrons are transferred from the hydrogen to the oxygen. In the fuel cell, these electrons are forced into an external circuit, which can then power a motor or other device. The reaction product thus formed is nothing more than pure water.

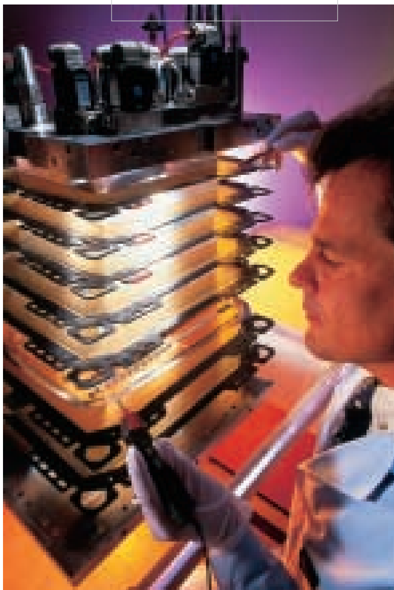


Fuel cells work at a high level of efficiency that, depending on the type, is also largely independent of the size. They are produced in many different variants. Nanotechnology can contribute much to this technique, such as ceramic films, nano-textured surfaces and nanoparticle catalysts.

In recent years around six to eight billion dollars has been devoted to developing fuel cell technology worldwide, and there is no reason to doubt that much will come of this technology. These quiet suppliers of electricity come in all sizes ranging from a postage stamp to a shipping container, and will by no means be used only in cars. For smaller consumers, a non-inflammable methanol/water mixture could be used as the hydrogen source, and would be filled up in the supermarket.

The fuel cell will help the electric motor to regain its pole position as the best possible motors of all (the first electric car took to the road in Paris in 1881). Only the electric motor can be operated at an efficiency level of over 90%, and only it can simultaneously function as a generator, and also convert kinetic energy back into electrical energy, such as when braking a car. The extremely good magnetic materials of new electric motors and generators are, naturally, also composed of nano-crystals.

Fuel cells will also be used in the household, supplying both electricity and heat at the same time.



Health

A breakfast with consequences in 2020:

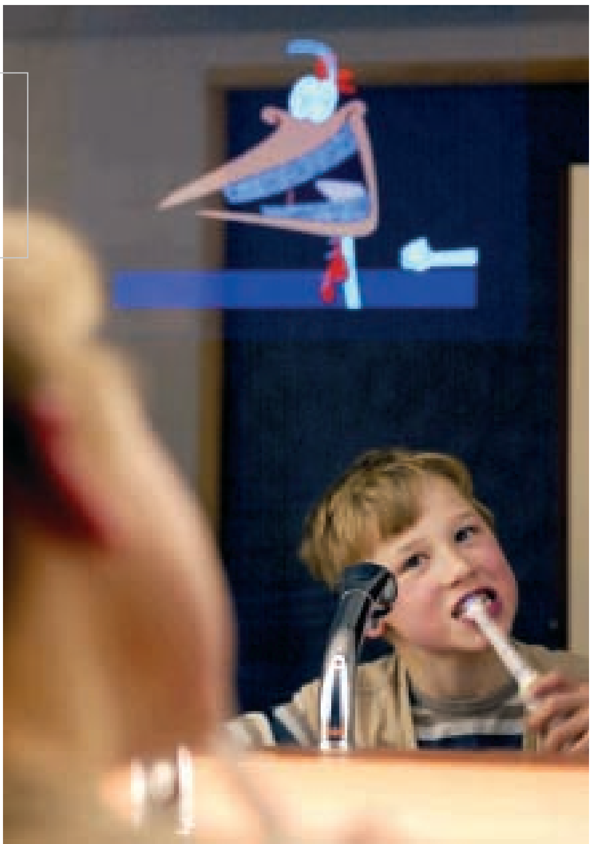
Is there any more coffee? Of course, and orange juice? Naturally, but there could be something very special about the packaging, such as an "electronic tongue" on the inside, which tests the juice to make sure it is still drinkable.

Or a sensor on the outside, which determines any possible calcium or other deficiencies from the fingers holding the packaging, which could then be remedied by "functional food". Or conventional goat's cheese – the OLED (organic light emitting diode) label on the packaging would recommend the correct one.

Top left: Film with nanoparticles keeps food fresh longer.

Top right: Intelligent packaging with polymer-based transponder chip.

The bathroom mirror is equipped with nanoelectronics, provides the user with information on request, and is somewhat reserved with regard to the orange juice, because orange juice is sugary, and sugar helps cause tooth decay. Once again nanotechnology is needed: the toothpaste (already available) contains nano-sized particles of apatite and protein, the natural material of the tooth, which helps it restore its normal condition (see also Biomineralisation).



The intelligent environment – the smart mirror equipped with nanoelectronics gives teeth-cleaning lessons.

The day cream (already available) contains nanoparticles of zinc oxide to combat harmful UV radiation. Being nanoparticles, they are completely invisible, so the cream is not white, but completely transparent.

Spies on the fingertip

With nanotechnology, nanoelectronics and micro-system technology, complex analysis equipment will become available that will also be within the price range of the private household. A tiny jab in the finger will be enough for future blood analysis. Are the cholesterol levels okay? Is the sugar level within the normal range? The findings could be emailed via Internet to the nearest nano-medical centre, where a more accurate analysis could be demanded or a completely individual medication put together via microreactors. In the body, the medication transports nanoparticles, which are coated in such a way that they only act at the source of the illness. "Drug delivery", accurate to the smallest detail. Doctors are watching the developments with great interest.

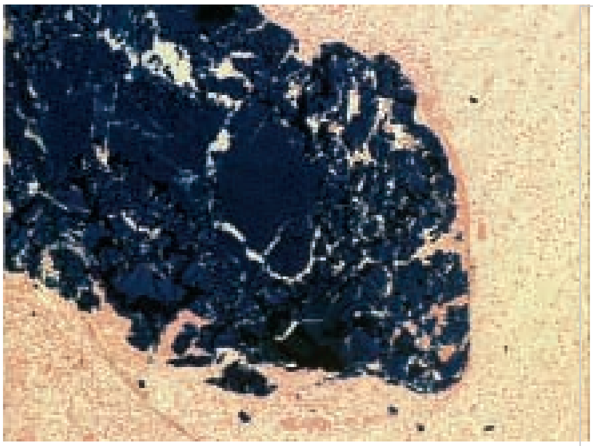
The diagnostics of tomorrow. The increasingly costly methods will be kept affordable by means of nanotechnology.

Supra-molecular medication capsules

The medications administered can in turn be extraordinarily sophisticated. They would be carried in supra-molecular hollow molecules (under development), nanoscale transport containers, which have antennae, to which antibodies of similar sensory proteins are attached. When they come into contact with structures typical of the agent responsible for the illness – for example, the outside of cancer cells or bacteria – they dock onto it and send a signal to the hollow molecule, which then opens up and releases its contents. With such nanotechnology, medications could be delivered in high doses direct to the source of the illness, without placing any stress on the rest of the organism and minimising side-effects.

Magnetic particles for cancer therapy

Similar tricks can be used to direct magnetic nanoscale particles to cancer sources, which are then warmed up by an alternating electromagnetic field and can destroy the tumour. Nanoparticles are also capable of passing through the “blood-brain barrier” filter system, so that they can also be used for combating brain tumours. This so-called magnetic fluid hypothermia was developed by the working group under the direction of the biologist Andreas Jordan. Clinical testing is now beginning.



Cancer cells in a glioblastoma brain tumour have “stuffed themselves full” with specially coated magnetite nanoparticles right up to the boundary with the healthy tissue. If the particles are now warmed up by an electromagnetic field, the tumour becomes susceptible to further treatment. Medical approval for this technique is already scheduled for 2005.

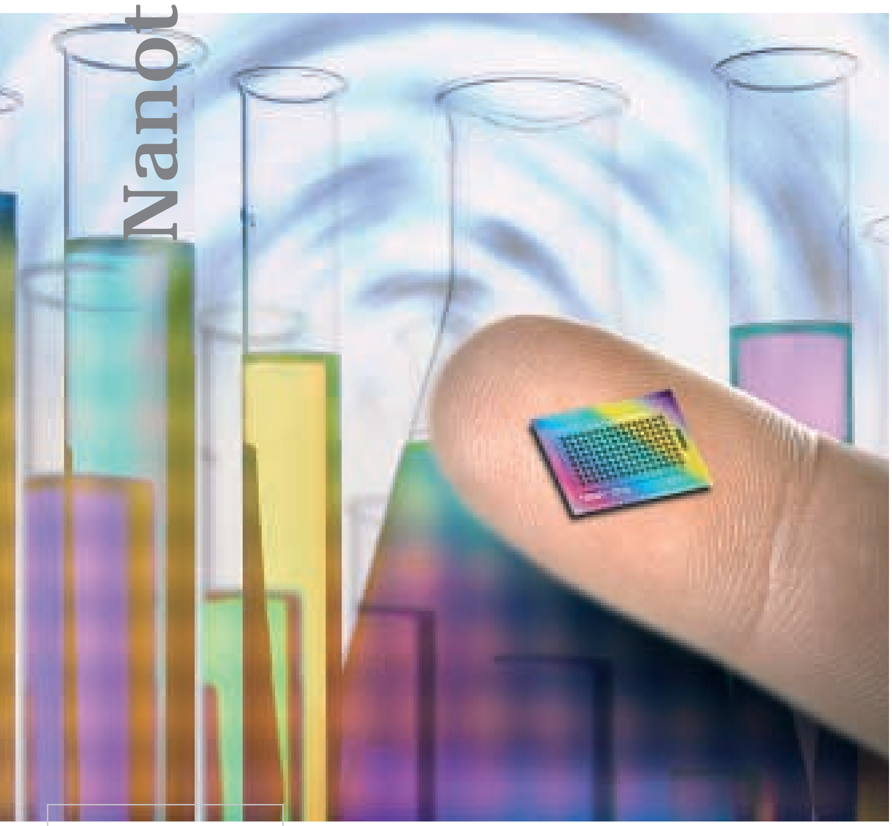
Turnstiles on a chip

Micro-system technology and nanotechnology – the boundaries between them are fluid – will pay for themselves in the medical sector, if in no other way, by miniaturising existing techniques and making them cheaper, sometimes by a factor of a hundred thousand or more. This would apply amongst other things to sophisticated machines that can check millions of cells, such as blood cells, for particular features at a rate of thousands

Health

Nanoparticle powders can be used to fire (sinter) perfect, reliable ceramic products, such as those used for implants.

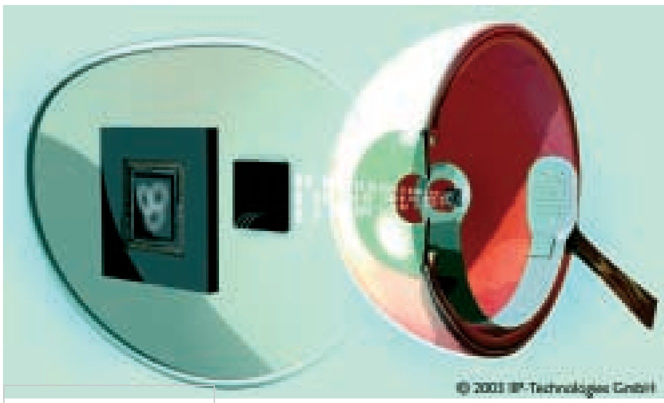
per second, and sort them in the living state. This could be done as follows: antibodies are added to the blood, which attach themselves to the cells of interest – and only to these cells – and at the same time carry a dye, which lights up or fluoresces under laser light. In the cell-sorter, the cells, encased in droplets, would be directed past such a laser; when a fluorescent signal is spotted, electrical fields steer the droplet and the cell into a collection vessel – the technique has been partly



Tiny but sophisticated, the "lab-on-a-chip", a laboratory the size of the fingertip.

borrowed from the inkjet printer. Cell-sorters are very sophisticated devices, combining micromechanics, optics and the most refined electronics, and such machines are correspondingly expensive. Nanotechnology will reduce these turnstile-sized cell-sorters down to the dimensions of a postage stamp, perhaps even making them disposable products. This will speed up medical progress significantly.

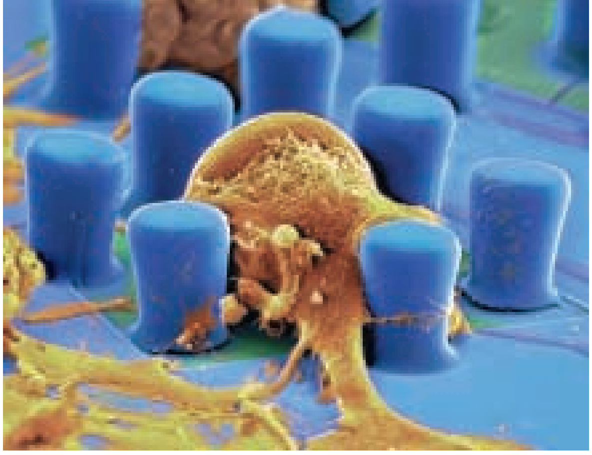
Even more sophisticated nanotechnology is planned for the lab-on-a-chip. According to leading developers, these will contain millions of nanodevices that work together in co-ordination to achieve their tasks. The chips would be several square centimetres in size, making them gigantic in comparison with the nano-machines they accommodate. This is due to the fact that fluids would have to circulate inside them, which in the nano-cosmos become as viscous as honey, and therefore need room to flow. Labs-on-a-chip will revolutionise biology, if scientists can in future use the nano-lab to follow what is going on step-by-step in individual cells. This would allow a sort of video to be reconstructed – a video of life. And scientists would not be satisfied with simply observing the cell, but would poke and prod it to see how it reacts, thereby decoding the mystery of life.

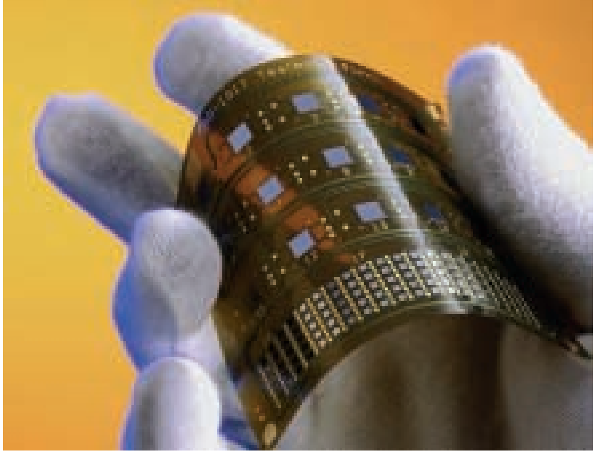


A retina implant.

Neuro-prosthetics

One extremely demanding application for micro-system technology and nanotechnology is currently entering the trial stage, the adaptive retina implant. This aims to restore partial vision in cases of blindness caused by *retinitis pigmentosa*. The system





Left: Coupling of nerve cells to electrical contacts.

Right:Wafer-thin silicon chips on flexible carrier material, for use in such things as intelligent labels, which can be incorporated into foodstuffs packaging or clothing.

consists of a tiny camera in the frame of spectacles, which transmits images of the surroundings to a special adaptive signal processor. The processor transmits this image data by wireless to the inside of the diseased eye. Here, a flexible film containing miniaturized electrodes in contact with the retina stimulates the optic nerve accordingly. If this development is successful, this will be the world's first "man-machine-interface" for the sense of sight. Many deaf people have already been helped by means of a cochlea implant. With nanotechnology, implants of this type will be able to be improved further.

Home care

Better nutrition and increasingly sophisticated medical care are enabling more and more people to live to an even greater age. This very desirable development however also brings with it the natural disadvantage that more and more people will need to rely on assistance. This will be able to be provided partly by nanoelectronics, and ideas under consideration include sensors and mini-computers woven into clothing and that would enable the continual monitoring of the state of health of elderly people – pulse, respiration and metabolism. If problems occur, the "MediVest" would automatically notify the family doctor or relatives. The location of the patient would also be reported by an integrated GPS or Galileo system module (Galileo is the future European version of GPS).

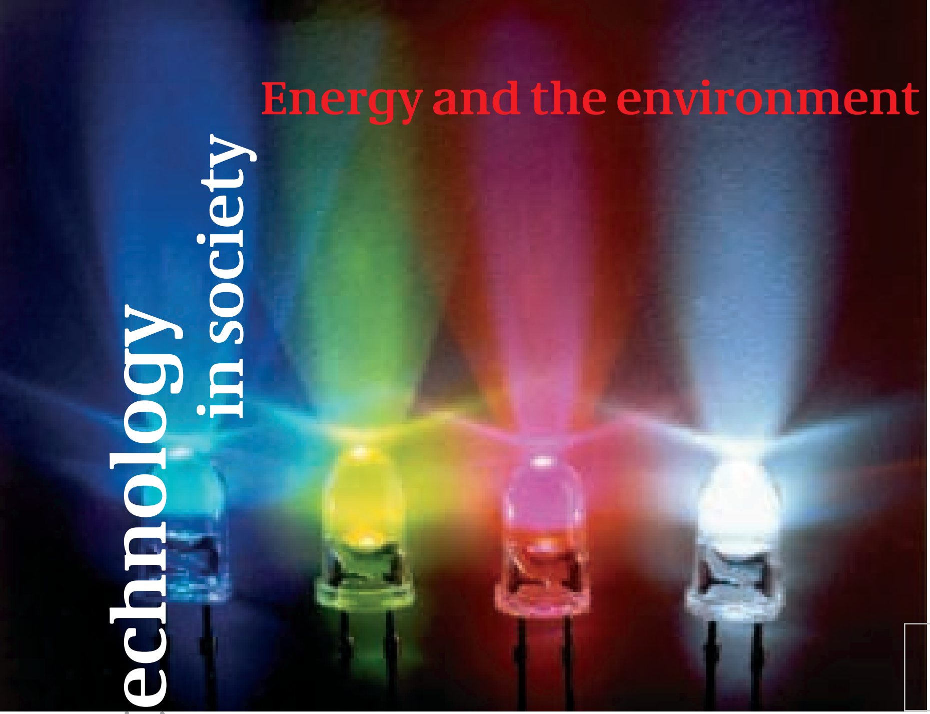
Automatic nurses

Old Europe" still has a rather reserved attitude toward mechanical helpers, although in Japan, mobile robots are approaching the industrial mass-production stage. It is quite possible that this could give rise to the development of automatic nursing machines suitable for everyday use, and work is already underway in this direction. Robotics will be able to handle the steadily increasing computing performance of nanoelectronics without any problem.

Robots with a sense of empathy from Oxford University. Enough for guarding ducks, but much more will be expected from automatic nurses.

Intelligent clothing: Integrated electronics play MP3 music files, provide directions in town and monitor the pulse – added value that can be experienced close up.

Energy and the environment



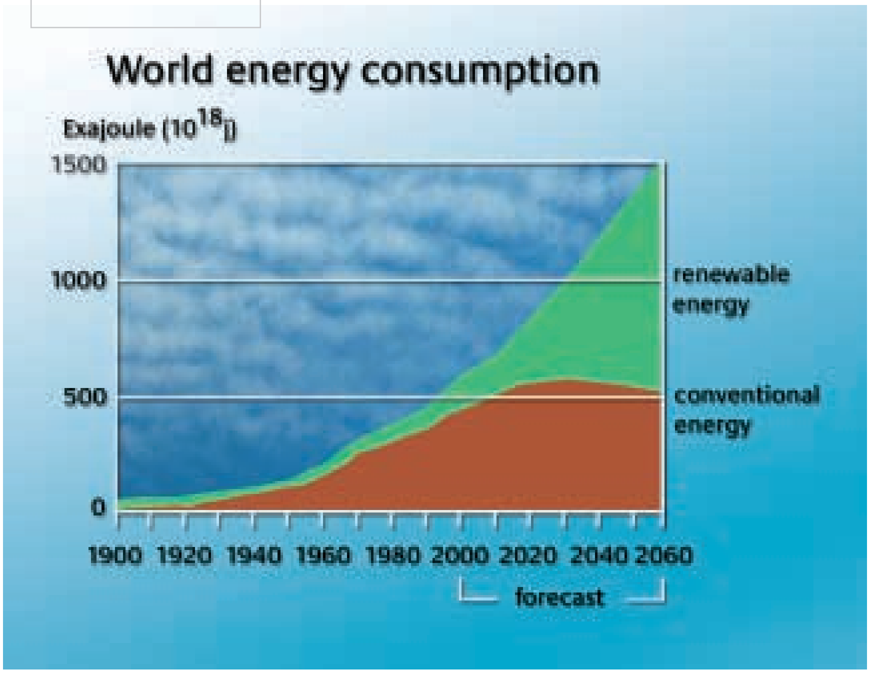
Efficiency revolution through LEDs.

In contrast to the previous history of technology, nanotechnology can combine economic growth with a reduced consumption of materials.

Business management à la nano: More convenience with lower material costs.

In Europe, about 10 percent of the electrical power produced is used for lighting. LEDs (light-emitting diodes) can now produce white light, and are therefore capable of replacing the conventional technology. Such a switch would result in substantial savings, because LEDs need only about 50 percent of the power required by a normal bulb in order to produce the same amount of light. This promises a considerable energy-saving potential for the lighting sector.

Forecast by Shell AG: Nanotechnology will be the technology of choice for renewable energies.



In private households, there are millions of television sets using cathode-ray tubes that will soon be replaced by sets using LCD (liquid crystal display) technology, and in the longer term also OLED technology. Both technologies have the potential of reducing the energy consumption by 90 percent. LEDs and OLEDs are produced with the aid of nanotechnology. If millions of households save a few kilowatts each, the result will be Gigawatts – the capacity of several large power stations.

The performance of fuel cells can be regulated quickly and easily. The first natural gas heaters equipped with fuel cells are now coming into use in the household, generating both controlled heat and electricity. Once millions of households are equipped with these devices, these heaters will be able to be combined via the national grid and the Internet into virtual major power stations, with a theoretical maximum capacity of

The complete spectrum: The glass facade of one of the halls of the Hotel Weggis on Lake Lucerne, illuminated in all the colours of the rainbow with 84 000 LEDs supplied by Osram.

hundreds of Gigawatts. In the long term, natural gas could also be replaced by hydrogen from renewable sources. Nanotechnology is ready for this development with new materials and catalysts.

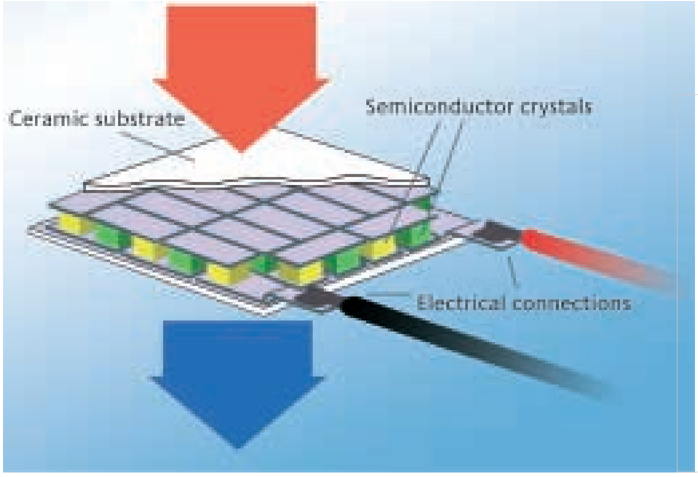
Ceramic membranes with nanoscale porosity are becoming increasingly important in the treatment of liquids, and also for the supply of clean drinking water. Bacteria and viruses can simply be filtered out with the aid of such membranes.

Nanotechnology will make solar energy a viable and lucrative proposition. Connective semiconductors of indium, gallium and nitrogen have already demonstrated performance figures that make solar cells with an efficiency level of 50% seem feasible. Efficiency is however only one criterion, nanotechnology will also enable a dramatic reduction in the cost of light collectors, either by thin-layer or particle technology. Laboratory samples of solar cell films produced with coating techniques similar to those used for LEDs and OLEDs, offer a performance of 100 Watts with a material weight of only 30 grams – a radical material reduction in energy production achieved in Leipzig by Solarion.

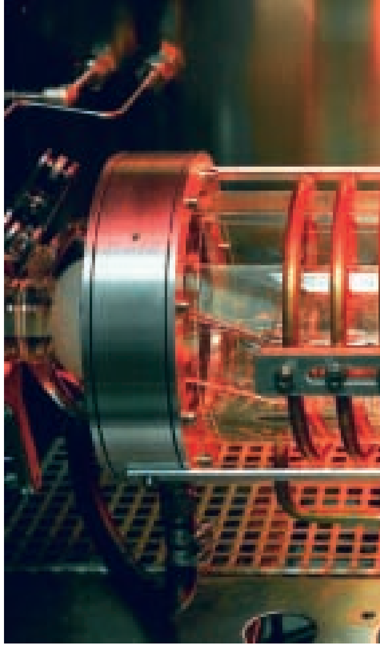
Siemens researchers claim an efficiency level of five percent for the latest organic solar cells, which can be printed on plastic film, and should become very affordable. The photoactive layer is only about 100-nanometers thick, and the working life is already several thousand hours of sunlight. The first products using this technology are expected to be on the market by 2005.

OLEDs (organic LEDs) will be used in many future displays.

Energy and the environment



Conventional thermoelectric module: a flow of heat is converted into electrical energy by blocks of semiconductors. Nano-structures are helping this technology achieve high levels of efficiency, thereby opening up new markets.

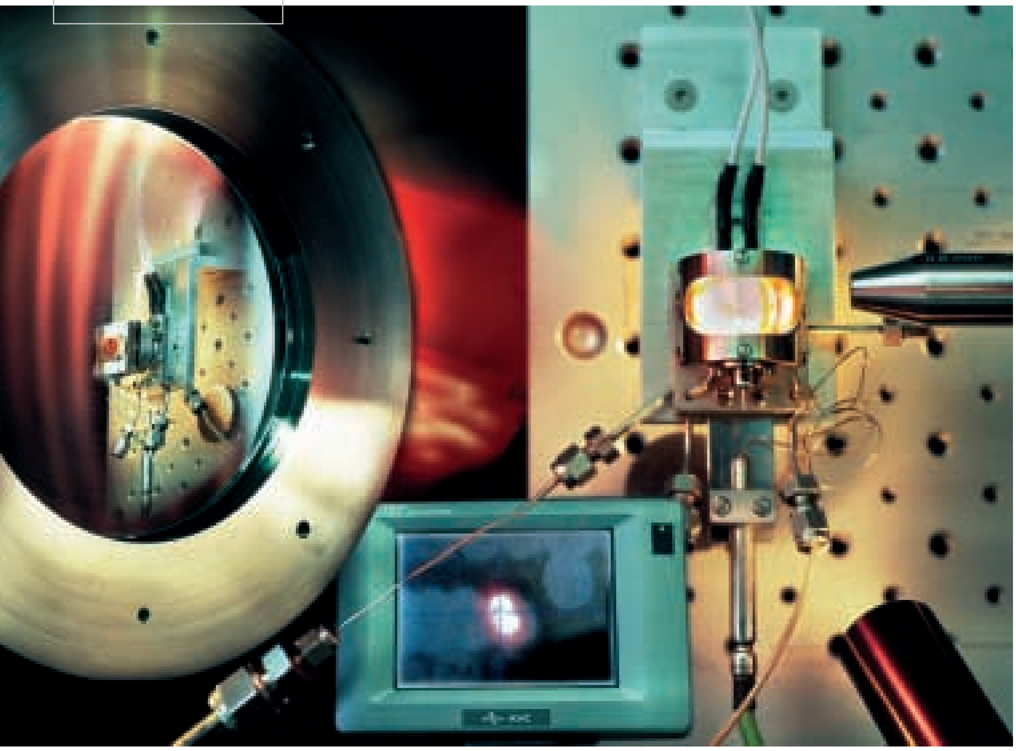


Nanotechnology is breathing new life into many old ideas that would otherwise have gone by the wayside due to the inefficiency of the available materials. One of these is the idea of thermoelectric electricity generation:

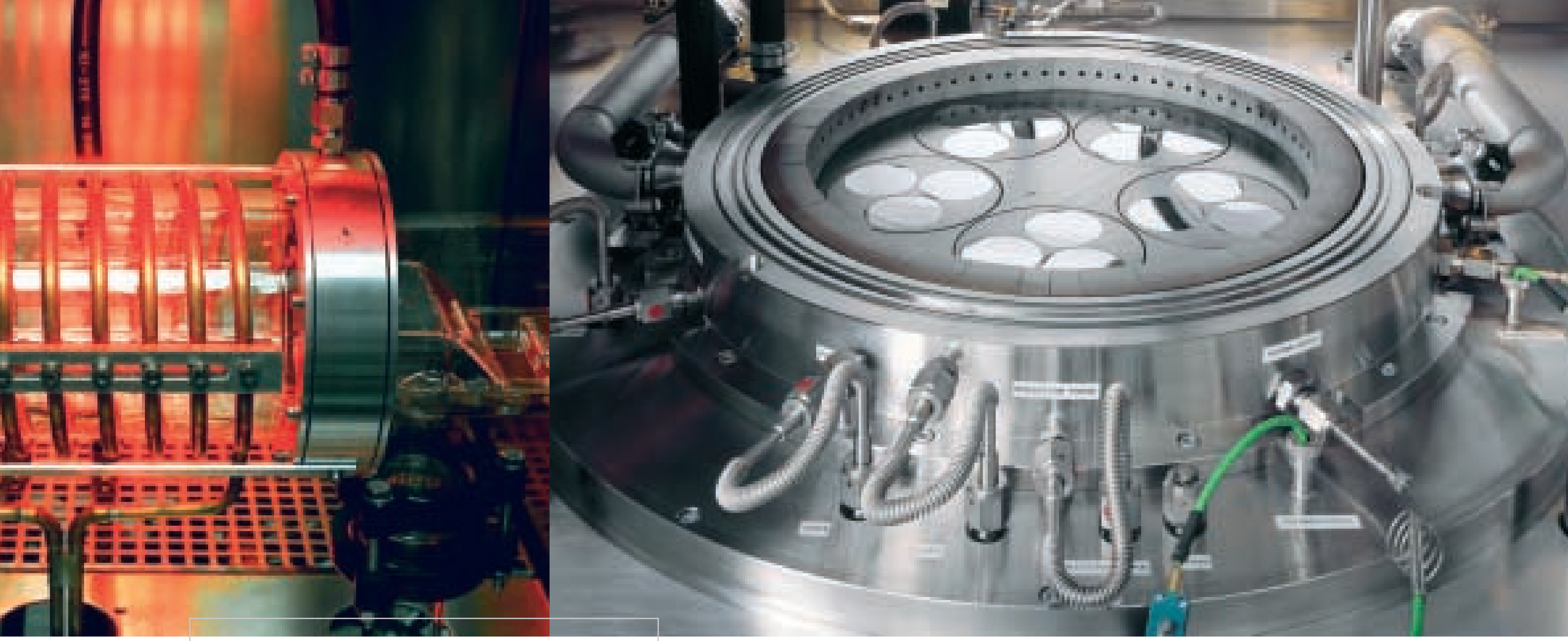
Electricity from heat, heat from electricity – Thermoelectrics

There is a wide range of known physical effects, hardly noticed by the public at large, that have performed only modestly in their various market niches. For example, the cooler bag, which is connected to the power supply system of the vehicle, and then really cools properly. Inside this, invisibly, works the legacy of Jean-Charles-Athanase Peltier, a French scholar, who in 1834 discovered the effect which now bears his name: a flow of current through the contact point between two different metals produces heat on one side of the contact, and cold on the other. Thirteen years earlier, the German Thomas Johann Seebeck had discovered the reverse effect, whereby a flow of heat through the contact point between two different metals generates electricity. Both these gentlemen are achieving new fame thanks to nanotechnology, which is now enabling the development of new materials that finally enable both these effects to work with very good levels of efficiency.

Chemical micro-reaction technology for the efficient production of even the most exotic substances.



The production of such materials again involves the same sort of machines used to manufacture LEDs. These machines apply a layer measuring five nanometres of antimony telluride to a nanometre-thick layer of



Aixtron reactors for research (left) and for the accurate production of thin layers of connective semiconductors (right).

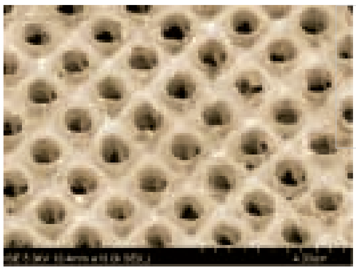
bismuth telluride, and then repeat the process until a semiconductor film has been created that would have amazed and delighted Messrs Peltier and Seebeck: when electricity flows through it, one side of the layering becomes hot, the other cold. The film can be structured very finely, so that it can be used for the accurate cooling of chips, or in a lab-on-a-chip in order to operate tiny reaction vessels, in which DNA is reproduced by means of rapid temperature change. It is quite conceivable that the dramatically increasing efficiency levels will in future make Peltier elements the technology of choice for the whole cooling industry. On the other hand, anyone with cheap sources of heat such as geothermal heat can produce electricity very economically with such thermoelectric layers. Iceland could become as rich as Croesus in terms of energy, thanks to electrolytically generated hydrogen.

In the chemical industry, techniques like this will be able to covert huge amounts of waste heat into electricity – silently, almost invisibly, and efficiently – with nanotechnology.

Thermo-photovoltaics

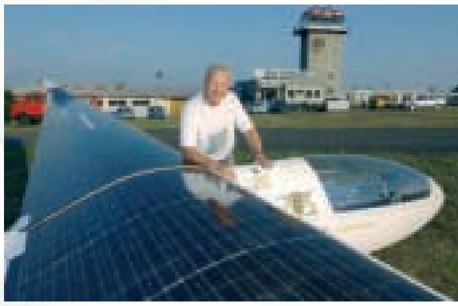
Thermo-electrics is not the only means of converting waste heat elegantly into electricity. Thermo-photovoltaics (TPV) use the (invisible) heat radiation, infrared radiation, of hot objects. The nanotechnology resides in the structures of the emitters, which adapt the spectrum of the heat source to the spectral sensitivity of the thermo-photovoltaic cells.

Candlelight is enough for thermo-photovoltaic cells to produce enough power to operate a radio.



Tungsten emitters with nano-structure surface for the adaptation of the infrared spectrum.

Nanotechnology for sport and leisure



The continual refinement of technology, which now includes the nanometric scale, is bringing back to life old ideas that would previously have been unfeasible. Amongst these is the concept of flight by means of solar power.

Icaré II, a solar-powered glider, can take the same stresses as a normal glider, and can start off under its own power.
Top: At the end of an unofficial record flight from Stuttgart to Jena.

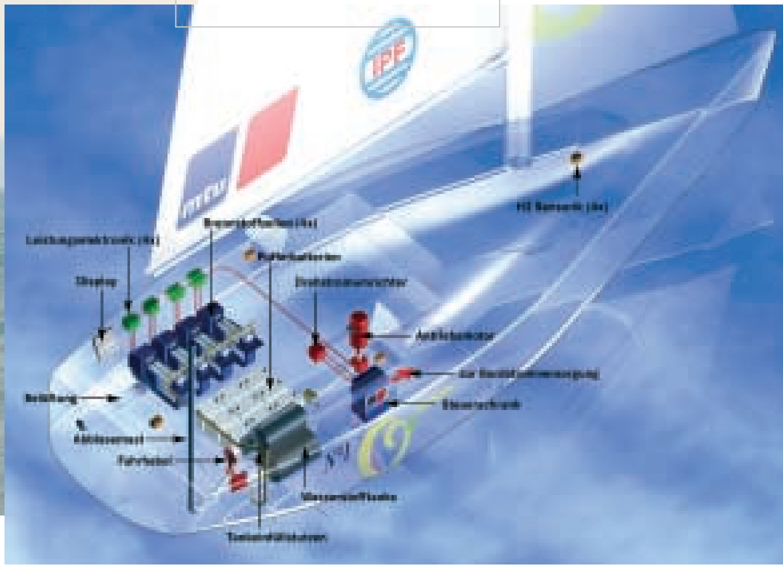
In June 1979, Bryan Allen propelled himself through the air in the Gossamer Albatross under pure pedal power across the English Channel to win the £100 000 Kremer Prize. The featherweight construction of the Gossamer Albatross by Paul MacCready was made possible by new materials. In 1981, a long-distance flight was made under pure solar power, although the aircraft, the Solar Challenger, was terribly fragile.

At the beginning of the 1990s, in memory of its unfortunate aviation pioneer Albrecht Ludwig Berblinger ("The tailor of Ulm"), the city of Ulm organised a competition to develop a practical solar-powered aircraft. In July 1996, the powered glider Icaré II built by the University of Stuttgart emerged as the clear winner.

NASA has designed a potential substitute for satellites in the shape of the HELIOS experimental solar aircraft, which is kept in the air by day by solar power, and at night be means of a "rechargeable" fuel cell unit. Maximum altitude: almost 30 000 metres.

In 2003, experts in thermodynamics, aerodynamics, electrical systems, composite materials, photovoltaics, energy conversion and computer simulation – nanotechnology is well represented in almost all these fields – met in Switzerland to discuss a project aimed at getting new technologies off the ground for an environmentally compatible future. Off the ground in the literal sense: around 2009, this ambitious project aims to take Bertrand Piccard and Brian Jones, who went around the world in a balloon in 1999, around the globe once more – this time non-stop in an aircraft powered only by solar energy!

Yacht with fuel cell engines by MTU, Friedrichshafen, Lake Constance. Nanotechnology can help such vehicles to combine efficiency with elegance: another conceivable idea is sails made of flexible textile solar cells, although the material would in this case have to be dark.

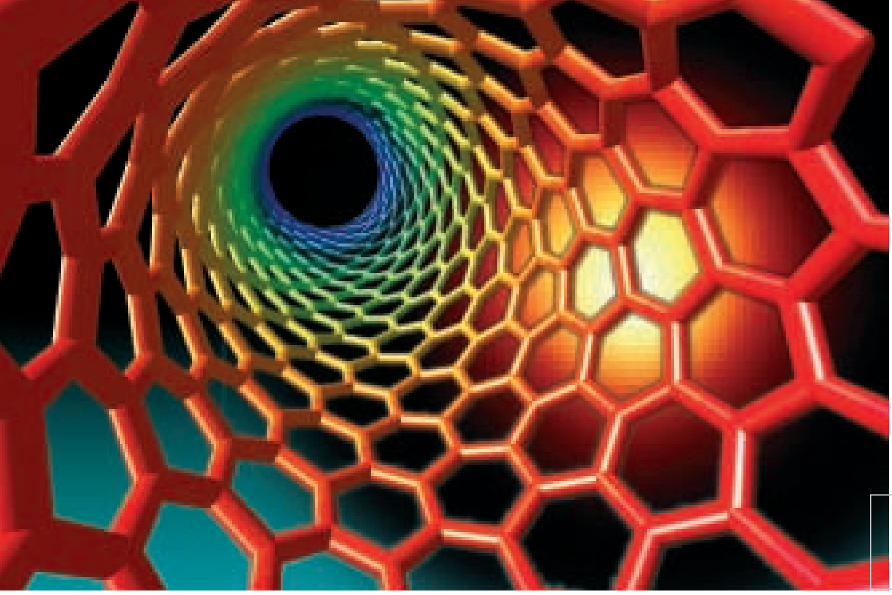


The "air worm" of the University of Stuttgart. This is planned to be used as a relay station for radio telephony.

Design study by the firm of Fuseproject, a fuel cell powers the scooter silently through the city.

The project could well earn these new technologies the respect they deserve, and also give rise to a whole range of new vehicles, such as solar-powered aircraft controlled by computers, sensors and GALILEO, which could also take novices into the air silently and without any exhaust gases. Freedom above the clouds will become boundless. Solar catamarans could well be planing across the Mecklenburg lakes; pedelecs, electrically assisted bicycles, will help elderly people into the saddle who otherwise might have some difficulty. Small electrical vehicles are deliberately being developed in many places to save the cities of areas undergoing rapid industrialisation from disappearing in a mire of exhaust fumes.

The solar catamaran built by Kopf Solardesign GmbH flies in and around Hamburg.



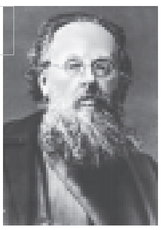
Visions

Nanotubes with Betelgeuse, a giant star in whose atmosphere fullerenes can be found.

The "finger street"

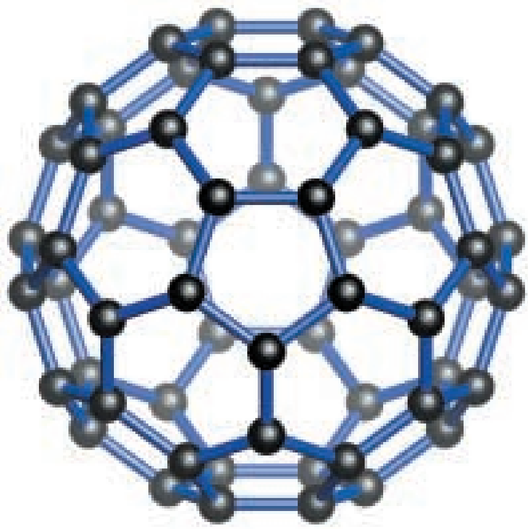
With nanotechnology, even the most utopian transport systems are conceivable, such as the "finger street". If practical artificial muscles become available – and work is going on in this direction at the moment – one could imagine a street laid out with signalling elements, fingers, which transport objects on them simply by beckoning. Like cell flagella, cilia, which fan dirt and foreign bodies out of the lungs, or propel slipper animalcules. The idea has room for many embellishments; tiny linear motors working according to this principle, which operate by means of plant muscles or "forisomes", are in any case being seriously considered. Other artificial muscle candidates include fabrics of carbon nanotubes. Even this idea is not so fantastic as the lift or elevator to the planets, which is being studied quite seriously by NASA, and which was first conceived by a Russian space pioneer, Konstantin Eduardowitsch Ziolkowski.

Konstantin Eduardowitsch Ziolkowski



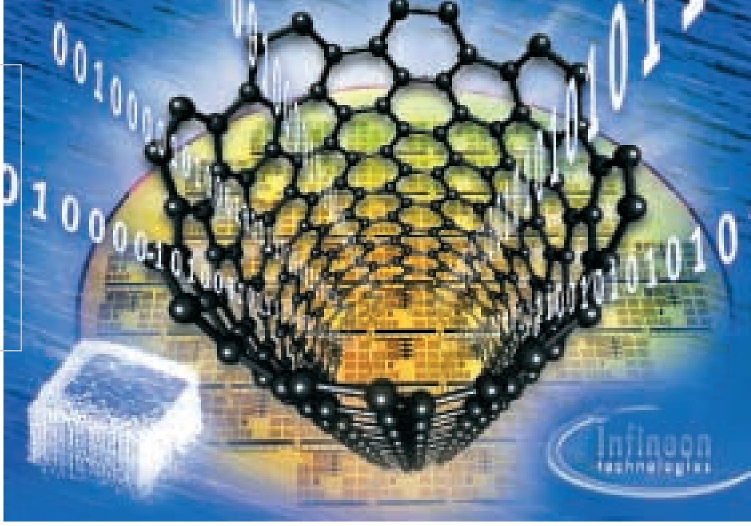
Carbon nanotubes for the lift into orbit

The recipe came from space: in the shells of old stars such as Betelgeuse, a red giant, many different elements circulate. If these react chemically with each other, nanocrystals form, such as silicon carbide, silicon oxide, corundum and even diamond, as is already known from the examination of meteorite that have formed from such dust. In order to find out more, scientists have reproduced the conditions in these star shells in the laboratory – and in 1985 found traces of a completely unknown substance. This proved to be a new compound of carbon: a hollow molecule very reminiscent in shape of a football. A recent look into the heavens showed that this molecule is also formed in the shells of stars.



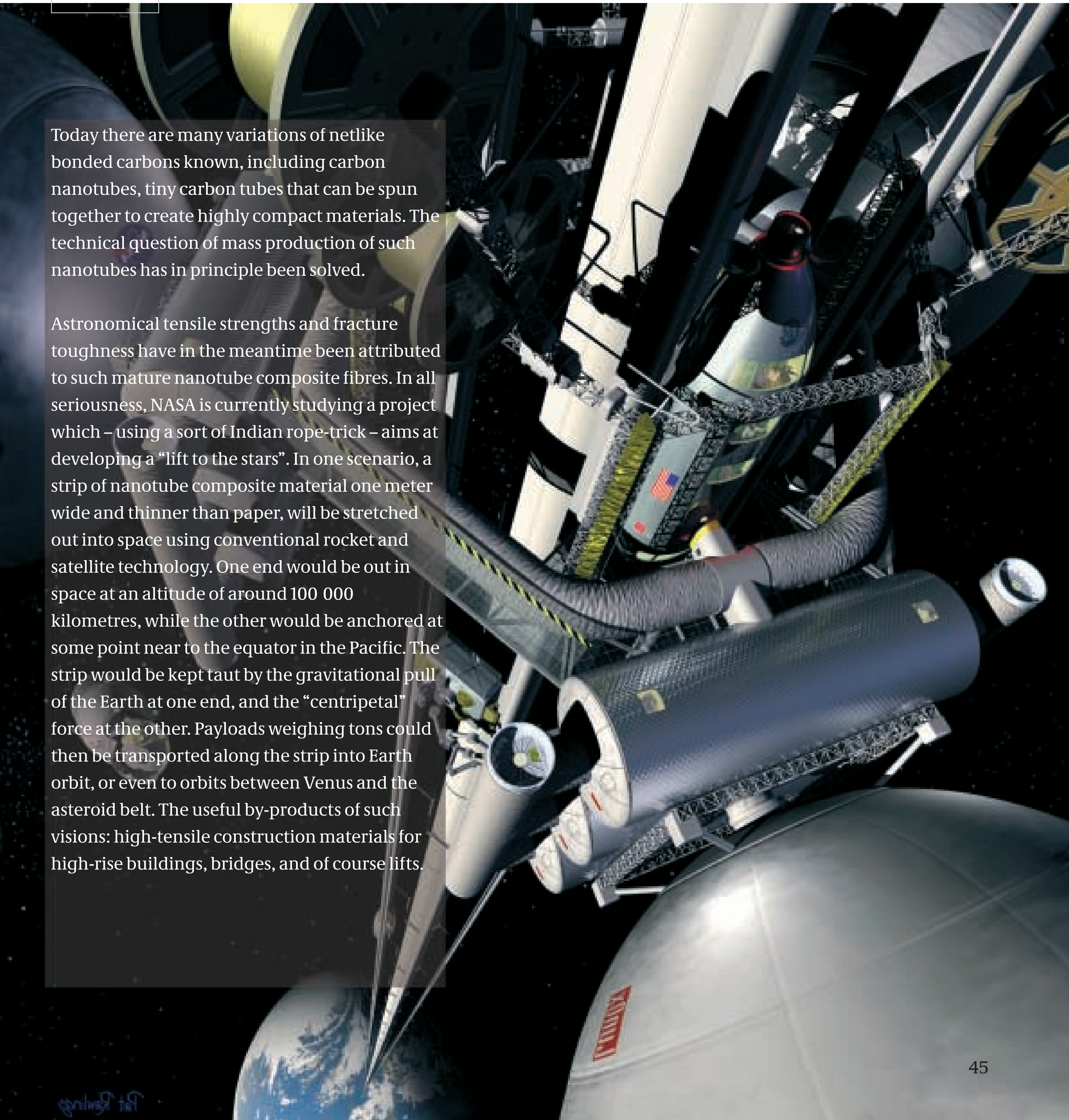
Fullerenes, cavities of carbon networks, hopeful prospects in the search for exotic materials.

Robert Curl, with fullerenes on his fingertips, which have won him a Nobel Prize.



Giant molecules as master computers: nanotubes could form the basis for the high-performance chips of the future.

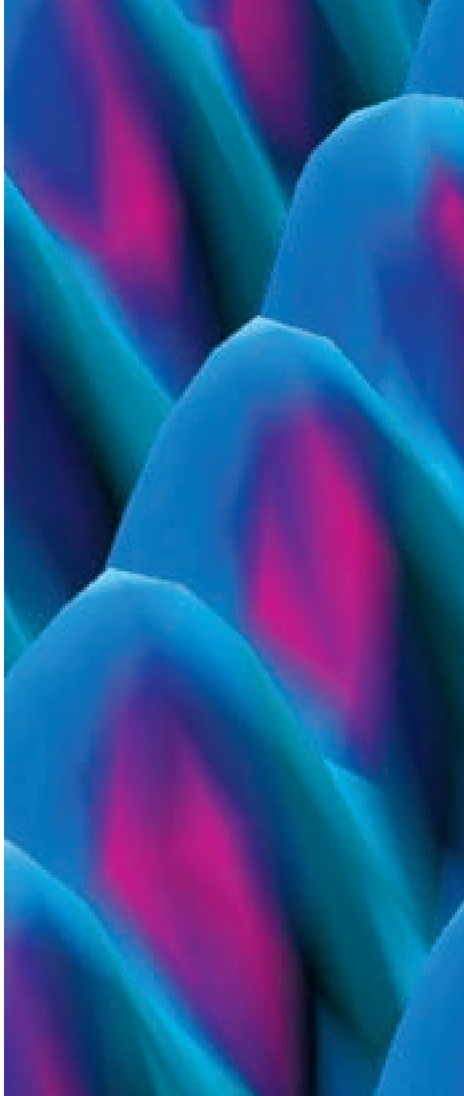
Vision: a lift to the planets.



Today there are many variations of netlike bonded carbons known, including carbon nanotubes, tiny carbon tubes that can be spun together to create highly compact materials. The technical question of mass production of such nanotubes has in principle been solved.

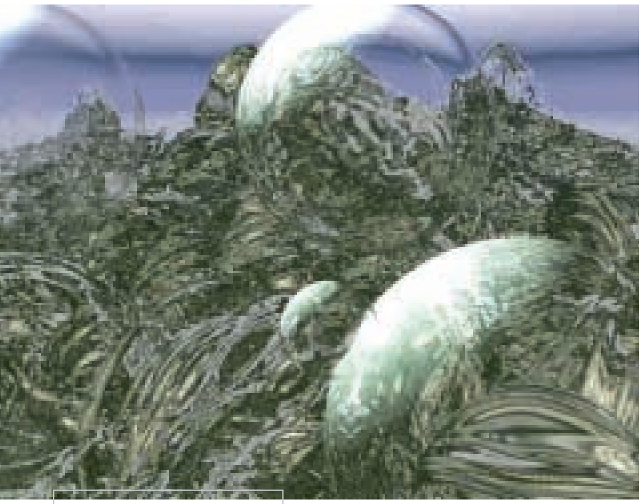
Astronomical tensile strengths and fracture toughness have in the meantime been attributed to such mature nanotube composite fibres. In all seriousness, NASA is currently studying a project which – using a sort of Indian rope-trick – aims at developing a "lift to the stars". In one scenario, a strip of nanotube composite material one meter wide and thinner than paper, will be stretched out into space using conventional rocket and satellite technology. One end would be out in space at an altitude of around 100 000 kilometres, while the other would be anchored at some point near to the equator in the Pacific. The strip would be kept taut by the gravitational pull of the Earth at one end, and the "centripetal" force at the other. Payloads weighing tons could then be transported along the strip into Earth orbit, or even to orbits between Venus and the asteroid belt. The useful by-products of such visions: high-tensile construction materials for high-rise buildings, bridges, and of course lifts.

Opportunities and risks



The potential of nanotechnology for good, or at least to make a profit, is clearly immense. Due to innovations in many areas of application, huge commercial potential is ascribed to nanotechnology. There are already several hundreds of companies in Europe involved in the commercial application of nanotechnology, providing jobs for tens of thousands of generally highly qualified employees. In this respect, scientists and businessmen are unanimous: nanotechnology is much more than just a new "hype".

Too good to be true? A super-colony, which appears possible as least in theory, has already found its way into literature: In Michael Crichton's best-seller "*Prey*", swarms of smart nanoparticles join together to form semi-intelligent beings, who turn on their creators. Another sombre vision of the American nano-prophet, Eric Drexler, sees the world threatened by so-called "gray goo", a gray cloud of wayward nano-robots.

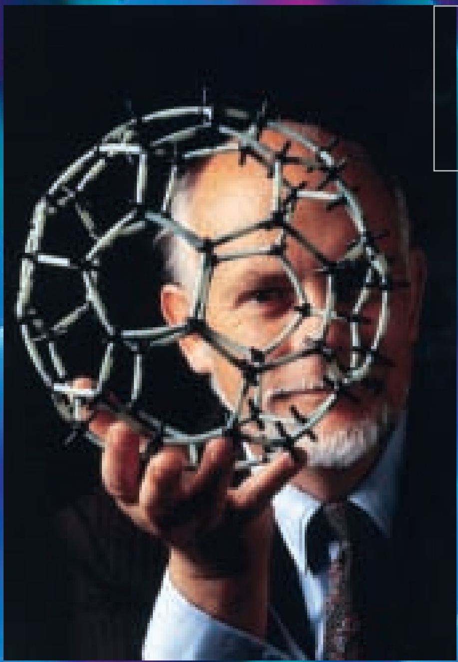


Due to the problem of the 'fat and sticky fingers, the "gray goo" scenario of Eric Drexler is just as unlikely as the idea that the world could be turned into jelly bears by nanotechnology.

Eric Drexler actually considers it possible to build nanoscale robots of a size of only a few millionths of a millimetre, program-controlled and capable of creating something new and bigger from the raw materials provided. And if the process got out of control, it would create, instead of something wonderful, this gray goo, which could be both contagious and dangerous for both man and machine.

This concept is not taken seriously by most experts. Like Richard Smalley, the Nobel Chemistry Prize winner of 1996, who points out the peculiarity of chemical bonds, which make it impossible for every atom or every molecule to be combined with each other.

This alone would make the idea of a nano-bot, a nanoscale robot or assembler, highly unlikely. In this case, if such an "assembler" were to put together matter atom by atom, it would have to use "fingers" to do this, which in their turn consist of atoms, and would necessarily have to have a certain minimum thickness. And this would not



Richard Smalley, winner of the Nobel Prize in Chemistry, considers the risks of nanotechnology to be containable.

only be to grasp the selected atom, all the atoms of a cubic nanometre would have to checked during assembly, where the fingers would necessarily get in the way. So much for the fat-finger problem. To this must be added the sticky-finger problem, the atoms grasped, depending on their type, could not be simply picked up and put down again, but would start to form bonds – a commonly known phenomenon: it is not so easy to get a sticky globule off your finger again. And these are essential arguments that cannot easily be circumvented. Mechanical nano-bots are therefore an impossibility. Richard Smalley could be right: there is no reason to fear that armies of wayward nano-machines could rampage over the world, turning it into gray goo.

But there could well be good reasons to fear that nanoparticles could also have undesirable effects on mankind and the environment. For instance, nanoparticles could be harmful to health due to their minute size, which even enables them to penetrate into body cells and even break through biological barriers (such as the blood-brain barrier). Since nanoparticles – like other ultra-fine dusts such as diesel soot in vehicle exhaust gases – are substances that can cause unknown side effects, scientific investigations must first be carried out to ensure that such particles are safe. So far, there is very little available knowledge on the safety of nanoparticles, so that outstanding questions must be answered as quickly as possible by means of relevant experiments by nano-researchers and toxicologists. However, the risks appear to be manageable, since nanoparticles found in nature are extremely "sticky". They bond together very quickly into large lumps, which the body can get rid of very easily. We already know of some nanoparticles that they are not harmful to health. They are therefore used in sun-protection creams as the light-protection factor, or are mixed with other materials in bonded form, so that the user does not even come into contact with individual nanoparticles. Industry is also applying suitable safety measures in order to exclude any health risks to its customers or its employees.

While visions of nano-bots are still completely hypothetical, the promises of material scientists working on the nanoscale appear very real. The first products are already in existence, such as high-sensitivity hard-disk reading heads with thin coatings of twenty nanometres or less. Nanoelectronics can already be found in every laptop. As a potent technology, nanotechnology will naturally also have side effects, making many simple tasks superfluous. Many new areas of activity will be created in their place. Lifelong learning is becoming increasingly important, but even this can be fun too – with nanotechnology.

How do I become a nano-engineer?

Anyone visiting a research centre where intensive work is going on into nanotechnology will be able to see all the disciplines of the natural sciences side by side: biologists, chemists, engineers of every specialisation, crystallographers, mineralogists, physicists – the common denominator is the level of the atom, and an essential part of the common language mathematics. The classical natural science courses can therefore all lead to nanotechnology, although nanotechnology is beginning to establish itself as an independent discipline, such as at the University of Würzburg. Anyone taking up the subject of nanotechnology, says Alfred Forchel of the chair of Physics of the University of Würzburg, need have no fear that they are following a short-term trend, (Extract 'abi 10/2003' of the University of Würzburg).

"Because the trend toward miniaturisation is no scientific fad, but already has a great deal of development behind it, it is probable that in many areas, applications will go down to ever smaller scales, from micro to nano so to speak, in every discipline ranging from information technology to chemistry. One does not need to be a clairvoyant to see that everything will continue to shrink in size – one example being construction elements – and indeed to the smallest size possible."

Physicists, chemists and other natural scientists can with justification claim that they have always been involved in some way with nanotechnology. The subjects of classical atomic physics, the molecules studied by the chemists, are all inhabitants of the nano-cosmos. With the experimental capabilities available today, such as the detailed atomic structuring of clusters, layers, chips as well as the availability of substances of the highest purity and the investigation of the tiniest biological structures – a cornucopia of completely new possibilities has been opened up that is also of great benefit to application engineering. Alfred Forchel assesses the professional prospects or nano-engineers as quite good:

"Of course, the opportunities of finding a job in our sector also depend on the buoyancy of the economy, just like any other field of business. But relatively small matters often make all the difference: if companies receive stacks of applications, it is naturally difficult to make oneself stand out. By offering practical training in industry, it means that there is at least one company that the student knows a little more closely. Our students can also write their diploma thesis while working in industry, putting them another step closer to a job. They also study at least one non-technical subject, such as business management, so that they also have some other basic skills important for professional life."

But for nano-engineers, there is no getting round a sound natural science training, including mathematics, either at Würzburg or anywhere else:

It is not enough to dream of developing a tiny submarine that can travel through veins. A huge amount of time and work must be invested before it gets to that stage. One must learn to describe things mathematically, and have a sound working knowledge of such basic skills as physics and chemistry. However, there is no reason to be intimidated: your nano-fantasies are sure to help you through.

The idea of the submarine in a person's veins was just a film: nanotechnology is a little different, but there can be real money in it.

Contacts, links, literature references

Please note that this brochure originates from the German research ministry BMBF. It was therefore initially written for a German audience. For links to European, other than German courses, literature and websites please check the internet portal on nanotechnology of the European Commission (www.cordis.lu/nanotechnology).

Study courses in nanotechnology in Germany:

Nano-structure technology in Würzburg
University of Würzburg
Website: http://www.physik.uni-wuerzburg.de/nano/
Contact: uerzburg.de" ossau@physik.uni-wuerzburg.de

Bio- and nanotechnologies in Iserlohn
Technical University of Südwestfalen
Website: http://www2.fh-swf.de/fb-in/studium.bnt/bnt.htm
Contact: YPERLINK "mailto:Werner@fh-swf.de" Werner@fh-swf.de

Molecular Science in Erlangen
University of Erlangen-Nürnberg
Website: http://www.chemie.uni-erlangen.de/Molecular-Science
Contact: hirsch@chemie.uni-erlangen.de

Master's course in Micro- and Nanotechnology in Munich
Technical University of Munich
Website: o/home.htm" http://www.fh-muenchen.de/home/fb/fb06/studiengaenge/mikro_nano/home.htm
Contact: sotier@physik.fh-muenchen.de

Nano-molecular Science in Bremen
International University Bremen
Website: http://www.faculty.iu-bremen.de/plathe/nanomol
Contact: f.mueller-plathe@iu-bremen.de

Nano-structure science – Nano-structure and Molecular Sciences in Kassel
University of Kassel
Website: http://www.cinsat.uni-kassel.de/studiengang/studiengang.html
Contact: masseli@physik.uni-kassel.de

Experimental Bachelor's course with the degree of Bachelor of Science in Biophysics or Nano-sciences in Bielefeld
University of Bielefeld
Website: http://www.physik.uni-bielefeld.de/nano.html
Contact: dario.anselmetti@Physik.Uni-Bielefeld.de

Degree course in "Micro- and Nano-structures" in Saarbrükken University of Saarland
Website: uni-saarland.de/fak7/physik/NanoMikro/InfoMikroNano.htm" http://www.uni-saarland.de/fak7/physik/NanoMikro/InfoMikroNano.htm
Contact: wz@lusi.uni-sb.de

Literature references:

BMBF-Programm IT-Forschung 2006 - Förderkonzept Nanoelektronik
Pub.: Federal Ministry of Education and Research; Bonn, March, 2002.

Vom Transistor zum Maskenzentrum Dresden, Nanoelektronik für den Menschen
Pub.: Federal Ministry of Education and Research; Bonn, October, 2002.

Nanotechnologie erobert Märkte- Deutsche Zukunfts-offensive für Nanotechnologie
Pub.: Federal Ministry of Education and Research; Bonn, March 2004.

Bachmann, G.
Innovationsschub aus dem Nanokosmos: Analyse & Bewertung Zukünftiger Technologien (Band 28)
Pub.: VDI Technology Center for the BMBF; 1998.

Luther, W.:
Anwendungen der Nanotechnologie in Raumfahrtentwicklungen und –systemen
Technology analysis (Vol. 43)
Pub.: VDI Technology Center, for the DLR; 2003

Wagner, V; Wechsler, D.:
Nanobiotechnologie II: Anwendungen in der Medizin und Pharmazie
Technology definition (Vol. 38)
Pub.: VDI Technology Center, for the BMBF; 2004.

Hartmann, U.:
Nanobiotechnologie – Eine Basistechnologie des 21.Jahrhunderts
ZPT, Saarbrücken, 2001.

Rubahn, H.-G.:
Nanophysik und Nanotechnologie
Teubner Verlag 2002

Werkstoffinnovationen für Industrie und Gesellschaft-WING
Pub.: Federal Ministry of Education and Research; Bonn, October 2003.

Internetlinks:

Nanotechnology portal of the EU
www.cordis.lu/nanotechnology

European Nanotechnology Portal
www.nanoforum.org

Nanotruck – The journey into the nano-cosmos
www.nanotruck.net

Internet travel adventure beyond the decimal point
www.nanoreisen.de

News and discussion on nanotechnology
www.nano-invests.de

Nanotechnology sponsorship of the BMBF
http://www.bmbf.de/de/nanotechnologie.php

Nanotechnology portal of the VDI-TZ
www.nanonet.de

Glossary

Byssus threads: Also popularly called “mussel silk” or “mussel’s beard. Technically sophisticated threads created by mussels to anchor themselves to surfaces. They are as elastic as rubber at one end, and as rigid as nylon at the other.

CNTs: Carbon nanotubes

Clusters: Clusters of tiny particles, in this case atoms. Clusters usually have different properties to the solid form of the same materials, amongst other things because clusters contain a larger proportion of surface atoms.

Diatoms: Tiny single-cell creatures occurring in fresh and salt water, with a very elaborate shell of silicon dioxide and water. Diatoms are capable of photosynthesis, and therefore also have light-conducting structures.

DNA: Deoxyribo-nucleic acid. Giant molecule in the form of a double-helix, which contains the information for the design of an organism and formulae for myriads of proteins.

ESEM: Environmental Scanning Electron Microscope – special scanning electron microscope that allows air and humidity in the sample holder. The lenses do not have to be specially treated with, for example, gold vapour.

Fibre-optic thread: Directs light through extremely transparent material over long distances, usually for data transmission, but increasingly also for energy transmission.

Forisomes: So-called plant proteins named after the Latin word for “door leaf”, which are being researched as candidates for nanoscopic artificial muscles.

Free electron laser: Generates laser light by means of an accelerated bean of electrons travelling in a vacuum tube.

Frequency doubler: Here, material that doubles the frequency of light, for instance converting infrared light into green light.

Fuel cell: Device in which hydrogen and oxygen (usually from the air) react without combustion to form water, producing electrical energy with a high level of efficiency.

Lab-on-a-chip: Highly complex chips, now in the final stages of development, which with the aid of micro-mechanics, micro-fluids, nano-sensors and nanoelectronics, can carry out complex examinations of cells that would other wise require the resources of a complete research institute. The name is also used for comparatively simple microscopically printed object carriers.

Leukocytes: White blood corpuscles, which defend the body by absorbing foreign bodies in the blood such as viruses and bacteria, and also cell remains or cancer cells, or as lymphocytes, produce antibodies. Antibodies are very specific, adhesive molecules.

Lithography: Here, the technique of producing microscopic structures, usually by means of photo-reactive coating, which is inscribed with beams of light or electrons, developed, and then reveals or conceals required parts of the surface for etching and other processes.

Mask: A type of transparent film containing the design and layout of a computer chip, which is then transferred lithographically onto wafers.

Micelles: Tiny spherical structures used by nature, in this case the mussel, as transport containers.

Micro-lens fields: Micro-optic elements important for such things as information transmission by means of light.

Phase: Here: Condition or state, such as arranged/random, or crystalline/amorphous

Photosynthesis: Green plants, algae and cyanobacteria (blue algae) obtain their energy by means of photosynthesis. With the aid of sunlight, they convert carbon dioxide and water into sugars and oxygen. Photosynthesis works at an astonishing primary energy yield of over 80 percent.

Piezo crystals: Piezo elements generate electricity when they are compressed or stretched, such as the ignition sparks in "electronic" lighters. Conversely, a piezo-electric crystal can be shaped by electric current down to fractions of the diameter of an atom.

Proteins: Large molecules composed of ribosomes from amino-acids, which act in cells partly as nanoscopic tools, partly as building materials, for everything from eye lenses to fingernails. The decryption of the proteome, the sum of all proteins and their interactions in a cell, is only just starting.

Quantum computer: Uses the characteristic rules of quantum mechanics in order to solve problems, such as information encryption, that are practically insoluble with conventional computers. Still in the theoretical stage.

Reflectins: Special proteins used by organisms to create light-reflecting structures.

Ribosomes: Nano-machines that can produce myriads of proteins, and controlled by a molecular strip with information from the genetic material DNA.

Semiconductor: Material whose electrical properties can be specifically adjusted, making it either an insulator or conductor. Semiconductors have become one of the most important components of modern industrial products such as computers and mobile phones.

Tunnel current: Current that should actually not flow, because it passes an insulating gap, but can flow in the nano-cosmos, although it then depends significantly on the size of the insulating gap. This effect has made the scanning tunnel microscope possible.

UV radiation: Short-wave radiation that enables the production of very fine chip structures.

Van-der-Waals bond: Weak chemical bond between molecules, whose ultimate cause is the properties of the empty spaces of the molecules. Van-der-Waals bonds also determine the properties of water, and thus all living processes.

X-ray radiation: Short-wave, electromagnetic radiation used amongst other things in crystal structure analysis to determine the nanoscopic shape of molecules.

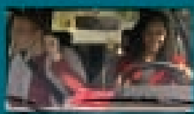
Pictures

P. 4 top: Kompetenzzentrum Nanoanalytik, University of Hamburg
P. 4 bottom: Lambda Physik AG, Göttingen
P. 5 top: Infineon Technologies AG, Munich
P. 5 bottom: BergerhofStudios, Cologne
P. 6 top left: Chemical Heritage Foundation
P. 6 top and bottom right, bottom left: BergerhofStudios, Cologne
P. 7 top left: NASA/ESA
P. 7 top right: DESY, Hamburg
P. 7 centre left: BergerhofStudios, Cologne
P. 7 bottom right: Institute for Experimental and Applied Physics, University of Kiel
P. 8 top left: REM-Labor, University of Basel
P. 8 picture sequence, from top: BergerhofStudios, Cologne; ditto.; ditto.; REM-Labor, University of Basel; Nobel Committee Stockholm (edited); DESY, Hamburg
P. 9 top left: Botanical Institute, University of Bonn
P. 9 top right: REM-Labor, University of Basel
P. 9 picture sequence, from top: BergerhofStudios, Cologne; ditto.; Fraunhofer Gesellschaft; Botanical Institute, University of Bonn; ditto.; TU Berlin, FU Berlin
P. 9 background picture: BASF AG
P. 10, top left + right: MPI für Metallforschung, Stuttgart
P. 10, centre right: ESA
P. 10, bottom left: MPI für Metallforschung, Stuttgart
P. 11, top left: Ostseelabor Flensburg, next: BergerhofStudios, Cologne
P. 11, top right: University of Florence, Italy
P. 11, centre right: Paleontology Institute, University of Bonn
P. 11, bottom left: BergerhofStudios, Cologne
P. 11, bottom right: SusTech, Darmstadt
P. 12, top, centre and right: Bell Laboratories, USA
P. 12 left: Chair of Biochemistry, University of Regensburg
P. 13, top: Institute for New Materials, Saarbrücken
P. 13, centre right: Degussa AG Advanced Nanomaterials
P. 13, bottom right: Institute of Geophysics, University of Munich
P. 13, bottom: Institute of Physical Chemistry, University of Hamburg
P. 14, top + bottom left: ESA
P. 14, bottom right: IBM Corporation
P. 15, top + centre left: Physics IV, University of Augsburg
P. 15, Graphic bottom right: BergerhofStudios, Cologne
P. 15, bottom: University of Hawaii, Honolulu
P. 16, left: Carl Zeiss SMT AG, Oberkochen
P. 17, top right: Carl Zeiss SMT AG, Oberkochen
P. 17, bottom left: IHT RWTH Aachen
P. 17, bottom right: Schott AG, Mainz
P. 18, top left: Bayer AG, Leverkusen
P. 18, bottom left: MPI for Quantum Optics, Garching
P. 19, all pictures: DESY, Hamburg
P. 20, top left: BergerhofStudios, Cologne
P. 20, bottom right: Institute for New Materials, Saarbrücken
P. 21, top left: HILIT, EU Joule III-Program
P. 21, top right: NASA/ESA
P. 21, bottom right: University of Stuttgart
P. 22, all pictures: BergerhofStudios, Cologne
P. 23, top left: National Semiconductor, Feldafing
P. 23, bottom right: Advanced Micro Devices, Dresden
P. 24, top right: Graphic: BergerhofStudios, Cologne
P. 24, centre left: Experimental Physics IV RUB, Bochum
P. 24, bottom: Institute for Experimental and Applied Physics, University of Kiel
P. 25, top right: Graphic: BergerhofStudios, Cologne
P. 25, bottom: IHT RWTH Aachen
P. 26, top right: IBM Corporation
P. 26, bottom left: Infineon Technologies AG, Munich
P. 26, bottom right: IBM/Infineon, MRAM Development Alliance
P. 27, top: Experimental Physics IV RUB Bochum
P. 27, centre: Kompetenzzentrum Nanoanalytik, University of Hamburg
P. 27, right: Chair of Nanoelectronics, RUB Bochum
P. 27, bottom: IBM Speichersysteme Deutschland GmbH, Mainz
P. 28: Siemens AG, Munich
P. 29, top right: Nanosolutions GmbH, Hamburg
P. 29, centre: Institute for New Materials, Saarbrücken
P. 30, bottom: Siemens AG, Munich
P. 30, top: DaimlerChryler AG
P. 30, bottom left: Fraunhofer Allianz Optical functional surfaces
P. 30, bottom right: University of Wisconsin, Madison
P. 31, top: Robert-Bosch GmbH, Stuttgart
P. 31, centre: Infineon Technologies AG, Munich
P. 31, bottom left: VW Press archive
P. 31, bottom right: Robert-Bosch GmbH, Stuttgart
P. 32, top left: Bayer AG, Leverkusen
P. 32, top right: Institute for New Materials, Saarbrücken
P. 32, bottom left: Keramag AG, Ratingen
P. 33, top: BASF AG, Ludwigshafen
P. 33, centre: MTU Friedrichshafen
P. 33, bottom right: Siemens AG, Munich
P. 34, top left: Bayer AG, Leverkusen
P. 34, top right: Siemens AG, Munich
P. 34, bottom: Infineon Technologies AG, Munich
P. 35, top left: Siemens AG, Munich
P. 35, top right: Siemens AG, Munich
P. 35 centre: Charité Berlin / Institute for New Materials, Saarbrücken
P. 36, top right: BergerhofStudios, Cologne
P. 36, left: Infineon Technologies AG, Munich
P. 36, right: IIP Technologies, Bonn
P. 37, top left: Siemens AG, Munich
P. 37, top right: Fraunhofer ISIT
P. 37, centre right: Oxford University
P. 37, bottom left, right: Infineon Technologies AG, Munich
P. 38, top left: OSRAM Opto Semiconductors GmbH, Regensburg
P. 38, top right: Audi/Volkswagen AG
P. 38, bottom: Graphic: BergerhofStudios, Cologne
P. 39, top: Park Hotel Weggis, Switzerland
P. 39, bottom: Siemens AG, Munich
P. 40, top left: BergerhofStudios, Cologne
P. 40, bottom left: Bayer AG, Leverkusen
P. 41, top: AIXTRON GmbH, Aachen
P. 41, right: Fraunhofer Institute for Solar Energy Systems, Freiburg
P. 42: Institute for Aircraft Construction, University of Stuttgart
P. 43, top left, right: MTU Friedrichshafen
P. 43, centre left: Institute for Aerospace Design, University of Stuttgart
P. 43, centre right: Fuseproject
P. 43, bottom: Kopf Solardesign GmbH, Hamburg
P. 44, top left: collage: BergerhofStudios, Cologne
P. 44, bottom right: RWTH Aachen
P. 45, top left: Siemens AG, Munich
P. 45, top right: Infineon Technologies AG, Munich
P. 45, bottom: NASA
P. 46, centre: BergerhofStudios, Cologne
P. 47: IBM Corporation, Insert: Siemens AG, Munich

EUROPEAN COMMISSION
Community research

European Industrial Research

Uncovering the secrets of nanotechnology





Films available from: http:/www.cordis.lu/nanotechnology

Contact:
Renzo Tomellini, European Commission - email: renzo.tomellini@cec.eu.int

Industrial technologies websites:
http://europa.eu.int/comm/research/industrial_technologies/index_en.html
http://www.cordis.lu/fp6/nmp.htm
http://www.cordis.lu/nanotechnology

European Commission

EUR 21151 — Nanotechnology – Innovation for tomorrow's world

Luxembourg: Office for Official Publications of the European Communities

2004 — 56 pp. — 21.0 x 29.7 cm

ISBN 92-894-7498-X

Venta • Salg • Verkauf • Πωλήσεις • Sales • Vente • Vendita • Verkoop • Venda • Myynti • Försäljning
http://eur-op.eu.int/general/en/s-ad.htm

15
KI5904968ENC

Nanotechnology is considered as the key technology of the 21st century. It can offer solutions to many current problems by means of smaller, lighter, faster and better performing materials, components and systems. Nanotechnology opens up new market opportunities and can also make some essential contributions to environmental and health protection.

The aim of this brochure is to illustrate to the public what nanotechnology is and thereby to stimulate the discussion. By describing the scientific background, technological developments, areas of application, and potential developments of the future, this brochure provides a complex and comprehensive picture of nanotechnology as we see it in our days.

ISBN 92-894-7498-X
9 789289 474986

Publications Office
Publications.eu.int