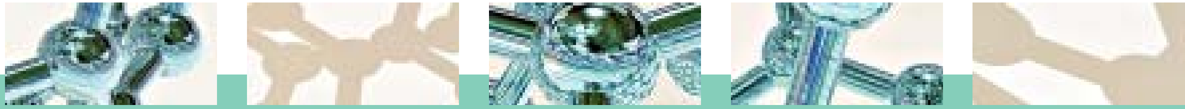

Lead article

Dwarfs with a giant future

Windows that never need cleaning, clothes that remain spotless, a perfect suntan without fear of the consequences – all thanks to nanoparticles. And that's just the beginning. Nanotechnology will bring benefits to all sectors of the economy, from car manufacturing to medicine. Experts predict an immense market for the products of this emerging technology.

It was the same daily ritual everywhere this summer, not only in the beach resorts: reaching for the sun lotion and applying it liberally to exposed skin in order to avoid sunburn. Many sunscreen products rely on tiny nanoparticles to provide the necessary protection against dangerous UV rays. These particles are too small to be detected by the naked eye. It takes a scanning electron microscope to see the incredibly small particles of zinc or titanium oxide, each only a few nanometers in diameter.

A nanometer is the billionth part of a meter. It's such an unimaginably small dimension that attempts to compare it with familiar objects inevitably sound far-fetched. To reduce the thickness of a human hair to one nanometer, it would have to be split into around 50,000 strands. But who would ever dream of doing that? And it doesn't much help the imagination to be told that the difference in scale between a nanometer and a football is the same as that between a football and the planet Earth. Yet despite the indescribably small size of these particles, they are expected to perform veritable wonders. Specialists hope to use them to make car paint that can change color at the flick of a switch, materials with tailor-made properties, or cancer drugs that can be delivered directly to the site of a tumor. Nanotechnology is about to trigger a revolution as far-reaching as the invention of the steam engine or the computer. "There's not a single area of our daily lives or a single sector of the economy that won't feel the effects of nanotechnology," pronounces nanoscientist Professor Wolfgang Heckl.

So what is so special about nanoparticles? "The nanoworld is subject to different laws than the macroworld. Familiar materials behave differently on the nanoscale. They take on different colors, and their melting point or electrical conductivity changes," explains Dr. Karl-Heinz Haas, who heads the Fraunhofer Nanotechnology Alliance. Ceramics become transparent, gold turns red, metals are transformed into semiconductors. Another unusual characteristic is that physical, chemical and biological laws merge into one at the atomic and molecular level, opening up new potential for interdisciplinary development work.

A great number of nano products can already be found on the market: Nanocoatings lend scratch-resistance to plastic lenses, a modified type of soot improves the road adherence of car tires, and novel filler materials with barrier properties give tennis balls a longer life. According to estimates by the Association of German Engineers VDI, nanotechnology products already generate more than 100 billion euros in annual sales, a figure that is expected to rise to more than 500 billion euros over the next five years. Market analysts at Lux Research estimate that the market for nanomaterials alone will reach a volume of 2.6 trillion dollars by 2014. To be sure of obtaining the largest possible share of this burgeoning market, the major industrial nations are investing massively in the new technology. Research spending on nanotechnology in the USA last year amounted to the equivalent of approximately 850 million euros. Japan's expenditure came to 800 million euros and Germany supported nanotechnology research to the tune of 300 million euros. A VDI study concludes that Germany has excellent scientific capabilities in this domain, rating third after the USA and Japan in terms of the number of published scientific papers. Where Germany falls behind is in the commercialization of this research, the experts warn.This is a shortcoming that the Fraunhofer Nanotechnology Alliance is making efforts to overcome. The

The scanning tunneling microscope provides images on the scale of individual atoms.
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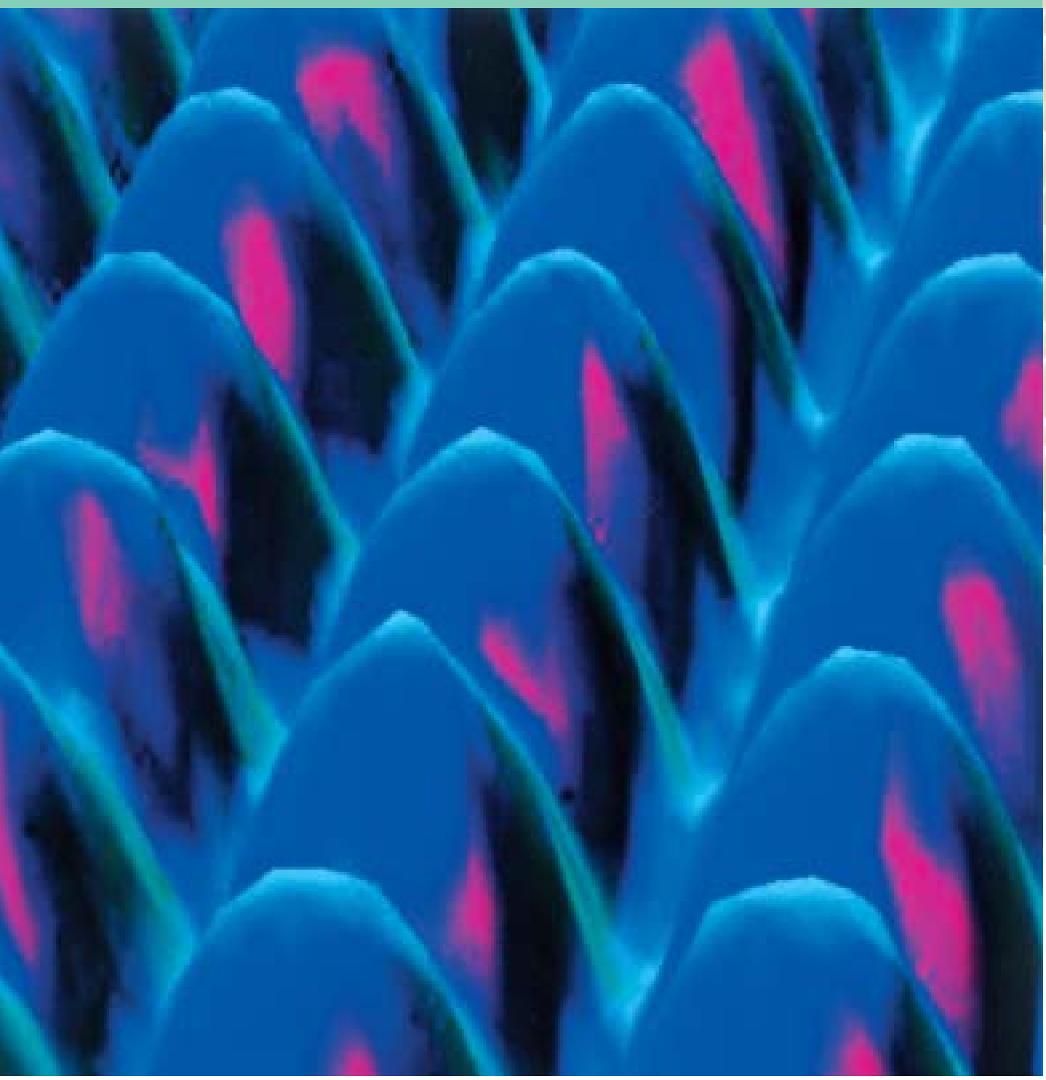
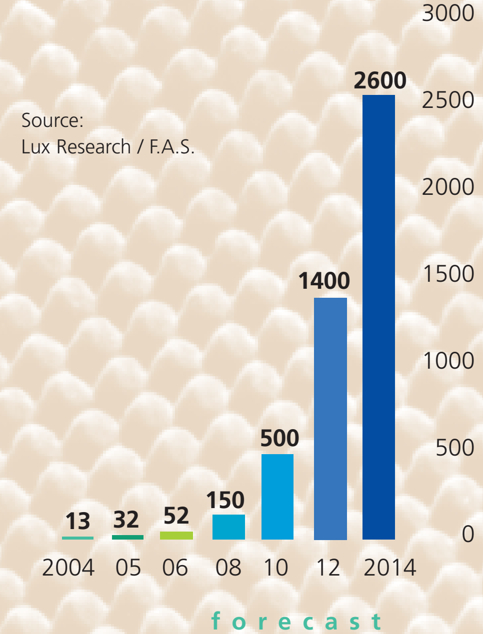


The future of nanotechnology
Sales in billion dollars



Alliance pools the expertise of over 20 separate institutes, with the aim of providing effective support to industry in its quest to develop new nano products. An area to which it gives special emphasis is research on nanocoatings. These ultra-fine coatings can modify the properties of surfaces to enable them to fulfill almost any desired function – scratch-resistant, dirt-repellent, electrically conductive or antibacterial.. This is an area in which commercialization is showing results. The Fraunhofer Institutes have achieved remarkable results in their work on conventional types of protective coating such as diamond and diamond-like carbon films, but also with their patented ORMOCER® nanoscale hybrid polymers. Such coatings, with a thickness of only a few nanometers, have long been used in the manufacture of hard disks and read heads for data storage devices. Optical coatings are also growing in importance. Microscopic structuring prevents the occurrence of unwanted reflections on display screens and increases the efficiency of solar cells. Researchers at the Fraunhofer Institutes ISE, ISC, IPT and IOF have developed new processes that now enable these fine structures to be applied to large surfaces . Hybrid polymers are being used in optical waveguides and micro-optical components.

The range of applications for thin films has expanded significantly in recent years. The Fraunhofer Polymer Surfaces Alliance is working on flexible ultra barrier coatings and polymer surfaces with antimicrobial properties. Ultra barrier films are required, for instance, in the manufacture of flexible displays made of liquid-crystal LEDs, organic polymer OLEDs and flexible solar cells. Antibacterial coatings are of interest to the food-processing industry and in medical engineering. Here the objective is to inhibit or prevent the deposition and proliferation of microorganisms such as bacteria, yeast spores and fungi. One way of killing off pathogenic bacteria involves the use of silver nanoparticles. When tweezers, catheters or implants are coated with nanoscale silver particles, microorganisms have little chance of survival. The nanoparticles destroy the enzymes that transport nutrients to the cells, destabilize the cell membrane, plasma or cell wall, and disrupt cell division. The researchers at the Fraunhofer Institute IFAM, working with Bio-Gate, a spin-off of IFAM and the University of Erlangen, have succeeded in manufacturing pure metallic silver in the form of ultrafine particles by using nanotechnology methods. These particles can either be incorporated in plastics or fluid products such as varnishes, or deposited on metallic components in the form of a nanocomposite coating.

The paint industry is another practical area for applications of nanosilver. In a joint research project with paint manufacturer Bioni CS GmbH, researchers at the Fraunhofer Institute ICT have successfully developed a non-toxic wall paint that provides walls and facades with long-term protection against attack by mold and algae. The new wall paint has been available on the market for a year now. The nanosilver particles mixed into the paint have a diameter of around 10 nanometers, or 1000 times smaller than the majority of fungal spores and germs. The particles have a very high surface energy that they tend to try to reduce by clumping together in larger agglomerates. "We prevent this by stabilizing them with additives and immediately incorporating them in a polymer system," says Helmut Schmid of the Fraunhofer Institute ICT. Another advantage of the polymers is that they facilitate the stirring-in of the silver particles into the suspension, ensuring their homogenous distribution in the paint.

Nanoparticles are frequently incorporated in polymers to make them easier to handle. These functionalized nanocomposites can then be processed using established manufacturing processes such as injection molding. Several Fraunhofer Institutes possess special expertise in the manufacture of nanocomposites, including IFAM, IAP, ICT and ISC. Polymer nanocomposites represent a new class of plastic materials that is likely to have a significant impact on future efforts to optimize and adapt materials to specific applications. Achieving a controlled, homogenous distribution of the nano filler materials in the polymer matrix represents the main challenge to developers of novel nanocomposites.

Nanocomposites are employed, for instance in a fire-resistant paint developed by IFAM researchers. The epoxy resin obtains its fire-resistant properties through a combination of organically modified nanoparticles and an organo-phosphorous flame retardant. The phosphor compound deprives the fire of oxygen and melts with the nanoparticles to form a crust that protects the coated object from burning. Another application involves the use of superparamagnetic nanoparticles to make rapidly hardening, easily removable adhesives. In another project, researchers at the IKTS are working together with colleagues from other Fraunhofer Institutes on thermoelectric nanocomposites intended for use in mobile power supplies, cooling and energy recovery.

But how are nanoparticles made? One way is to crush materials by grinding, a technique that has actually been in use for centuries. Ink is nothing else but minute particles of soot incorporated as a fine suspension in liquid. Another method is to build them up out of single atoms and molecules, the same way as in nature. Using a scanning tunneling electron microscope, it is possible to see single atoms and move them around and connect them using a fine-tipped probe. The inventors of this scientific instrument Gerd Binnig and Heinrich Rohrer, received a Nobel Prize for their work. Another technique employed is the sol-gel process, in which minute particles form in a liquid solution. This method is used to produce hybrid polymers such as the ORMOCER®s developed at the Fraunhofer Institute ISC. In this case, the nanoparticles form in situ in the matrix, doing away with the problem of dispersion. Hybrid polymers have been in use for ten years as light-hardening dental fillings for dental restoration work. They are extremely conductive, stronger than steel, lighter than aluminum and twice as hard as diamond – and those are just a few of the amazing properties of carbon nanotubes, CNT. The tiny tubes made up of carbon atoms were discovered in 1991 by Japanese researcher Sumio Iijima. They have a diameter of between 2 and 10 nanometers and can be produced in lengths of up to several hundred micrometers. They exist as single-wall, double-wall or multi-wall nanotubes The extraordinary material properties of nanotubes have driven researchers to equally extraordinary flights of fantasy. They dream of super-robust fibers that will enable them to build an elevator to space, or extremely miniaturized electronic circuits. But hardly any products have yet been realized, because the material has one serious drawback: Carbon nanotubes are very difficult to bind or mix with other materials, and they are still very expensive to make. Engineers at the Fraunhofer Group TEG have developed a low-cost technique for processing the hard-to-tame material. The TEG and IGB have set up a joint laboratory for

CNT applications, where they manufacture CNT precursors in the form of paper. The sheets look like black carbon paper and cost only a few euros per square meter. “But we are not restricted to any particular form,” stresses project manager Ivica Kolaric. The CNT composites can be mixed with a variety of different materials and combined as easily with plastics as with textiles. One of the first products containing CNT precursors from the TEG are the Völkl DNX range of tennis rackets. Carbon nanotubes are used to strengthen the frame at the points subject to the greatest stress, and they improve the tennis racket’s energy-absorbent properties.

A project by the name CarNak – Carbon Nanotube Actuators – aims to use CNT in adaptronics applications. Researchers at eight Fraunhofer Institutes are working together on this project under the leadership of the ISC. They aim to exploit a special

Nanosystems as part of tomorrow’s everyday world.
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property of carbon nanotubes, namely the fact that they become elastic when a current is applied. The main advantage of CNT actuators as opposed to piezoceramic systems is that they only require a very low control voltage of a few volts at most. To enable the CNTs to stretch, they have to be injected with electric charge-carriers. ISC researchers are working to develop new electrolytes suitable for this purpose. The preferred type of carbon nanotube for actuator functions is the single-wall variety. However, the synthesis of SWNT materials still needs to be scaled up from the laboratory to an industrial format. Three different synthesis routes are being tested at present: Arc- and plasma-assisted gas-phase synthesis at the Fraunhofer Institute IWS and combined PVD/CVD at the IFAM. Actuation mechanisms are being investigated by a research team at the IWM, using computer-based multiscale simulations. Simulation provides a means of identifying the most promising development routes before actual implementation. The biocompatibility and toxicity of the CNTs are being investigated by researchers at the Fraunhofer-Institute IGB, while a team of scientists at the Fraunhofer Institute LBF is testing their reliability.

Reliability testing of nano products is a difficult task, owing to the fact that materials behave very differently in the nano world than on a macroscopic scale. In order to be able to assess a nanomaterial’s lifetime and quality, established methods have to be combined with innovative concepts. Fraunhofer researchers are devising reliability testing concepts for nano and micro composites in a project named “Nano-Z, nano reliability”.

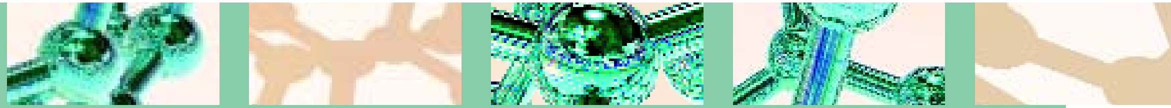
The leap from microelectronics to nanoelectronics represents a huge challenge to the semiconductor industry. At the Fraunhofer Institute CNT, science and industry are working together. Their aim is to accelerate the scale-up to industry of innovative process-step solutions as well as analysis and test/measurement processes for use in the manufacture of nanoelectronic components such as processor and memory chips.

Medicine is an area where nanotechnology is likely to bring about significant changes. The medical profession and the pharmaceutical industry have long dreamed of therapeutic drugs that are capable of making their own way through the body to a specific site, where they would act precisely on the targeted diseased cells. Nanotechnology might turn this vision into reality. Biological entities – tissue, cells, blood corpuscles – provide numerous models for polymer nanosystems. Synthetic polymer materials designed to imitate biological structures are excellently suited for use as drug carriers. By tailoring their surface and structures, these particles can be guided and delivered to a specific site. This process is called drug targeting. Consequently, the drug is not only delivered to the appropriate site but also released at a specified time, a controlled release. Scientists at the Fraunhofer Institute IAP are working on systems of this type, in a joint project with colleagues at the Max Planck Institute for Colloids and Interfaces and the University of Potsdam. Their research focuses on synthesizing and testing polymers for potential use in drug delivery systems manufactured on the basis of nanocarriers, in copolymers for non-viral gene vectors, and in functional colloids for magnetic resonance imaging, MRI.

A team at the Charité research hospital in Berlin aims to employ nanoparticles to improve an existing form of cancer therapy, which destroys tumors by evenly superheating the affected tissue. Before the radiation treatment, a fluid containing a suspension of magnetic nanoparticles is injected into

Nano everywhere?

The prefix “nano” is derived from the Greek word “nanos”, which means dwarf. In science, it designates the billionth part of a unit (10^{-9}). Richard Feynman, famous for his 1959 lecture entitled “There's Plenty of Room at the Bottom”, is considered the father of nanotechnology. Nanotechnology first took off as a scientific discipline in 1981, with the construction of the first scanning tunneling microscope. This instrument not only permits the visualization of atomic structures but also allows atoms to be manipulated using a fine-tipped probe. In 1986, Heinrich Rohrer and Gerd K. Binnig of the IBM research laboratory in Zurich received the Nobel Prize in Physics for the development of the scanning tunneling microscope (STM). In 1991, Japanese researcher Sumio Iijima discovered microscopic tube-like structures made of carbon atoms that possessed remarkable properties – carbon nanotubes. Nanotechnology is not restricted to any particular sector of industry or area of technology. Applications are being developed by biologists, chemists, physicists, materials scientists, computer scientists and medical scientists. Nanotechnology is an enabling discipline that covers a wide spectrum of new materials, components and systems with functions and applications based on specific properties that only appear on the nanoscale.



the tumor. The particles are enveloped in an outer layer of sugar molecules, enabling them to be taken up directly by the cancerous cells. Then a high-frequency magnetic field is activated, as a result of which the particles become mobile, generating heat through friction. This weakens the cancerous cells, enabling them to be destroyed by means of chemicals.

Researchers at the Fraunhofer Institute IGB are working on an alternative solution. In addition to their research on nanocarriers, which transport drugs inside them to the site at which they are to be released, they are also investigating novel active drug ingredients. Their cancer-therapy solution consists of functionally binding tumor necrosis factor , TNF, cytokines to a nanocarrier. These membrane signaling proteins trigger programmed cell death in tumor cells. Working with colleagues at the University of Stuttgart's Institute of Cell Biology and Immunology, the researchers have succeeded in binding bioactive cytokines (TNF) to core-shell nanoparticles. "These cell-like structures have a fixed nucleus surrounded by proteins that track down and destroy cancerous cells," explains Dr. Günter Tovar of the Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB. "To manufacture these particles, we exploit the self-organizing properties of the 'components': once contact has been established between the particles and the proteins, the nuclei grow without any further intervention." The resulting NANOCYTES® have already been tested on cultured human cancer cells, with success. The bioactive nanoparticles dock with the cancer cells and trigger programmed cell necrosis. Nevertheless, it will be a relatively long wait until NANOCYTES® technology can be employed in the fight against cancer in clinical practice, for nanomedical research is work-intensive and time-consuming.

Nanotechnology Alliance

Over a third of the 58 institutes belonging to the Fraunhofer-Gesellschaft are active in the field of nanotechnology. Their many and varied skills are concentrated in the Fraunhofer Nanotechnology Alliance. The major topics addressed by the Alliance include multifunctional coatings, for instance for the automobile industry, the design of special nanoparticles for biotechnology and medical applications, and the use of carbon nanotubes as actuators.

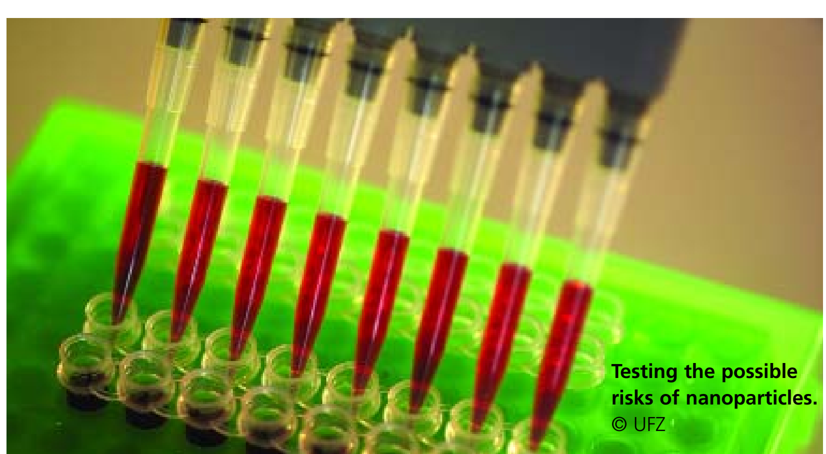
nano.fraunhofer.de

Nanotechnology is not without its detractors, however. People are worried about what happens when nanoparticles are absorbed by our bodies and what effect they might have on the environment. It was in order to provide answers to these questions that the German research ministry launched its funded projects "NanoCare", "INOS" and "TRACER". Ultrafine particles that represent a possible danger to the human body have been around since long before nano products were invented. Fine particulate matter is also released by all combustion processes. Many studies, including one conducted by the Fraunhofer ITEM, indicate that the smaller the particles are, the deeper they penetrate the lungs during respiration.

One thing is certainly clear: "People are coming into contact with nanoscale materials on many fronts, not only through their use in pharmaceutical products. They are already being employed in processed foods, cosmetics and a variety of other products. The increase in production of metal oxides and carbon nanotubes, for example, goes hand in hand with increased exposure to such materials in the workplace," warns Prof. Dr. Harald Krug of the national research center in Karlsruhe. To assess the possible risks, Fraunhofer researchers at IGB working on the TRACER project are evaluating the biocompatibility and cytotoxicity of carbon nanotubes throughout the value chain – from their manufacture to the finished polymer composite. Another group of researchers at the Fraunhofer Institute IKTS is studying how easily nanoparticles can penetrate the skin, lungs, intestine and nervous system, in collaboration with other partners in the INOS project on the identification and assessment of the impact of engineered nanoscale particles on human health and the environment. The project findings are being published in an openly accessible database, where anyone can find information on the potential risks of nanoparticles. The environmental impact of nanoparticles of materials such as titanium dioxide is being closely studied by researchers at the Fraunhofer Institute IME.

The Fraunhofer-Gesellschaft intends to expand its activities in the domain of nanotechnology still further. It plans to set up an innovation cluster "Nano for Production" in Dresden, in which universities, Fraunhofer Institutes and industrial partners will collaborate on the development of new solutions. Close cooperation between science and industry is an essential factor in enabling researchers to translate their already excellent research work into practical applications more rapidly and efficiently. It is only on this basis that German companies will be able to benefit to the maximum from the huge opportunities opening up in the emerging market for nanotechnology products.

Birgit Niesing



Testing the possible risks of nanoparticles.
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