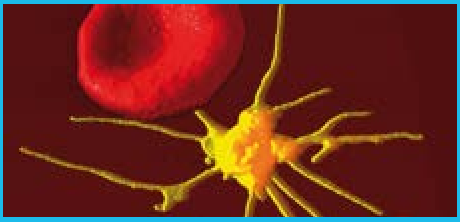
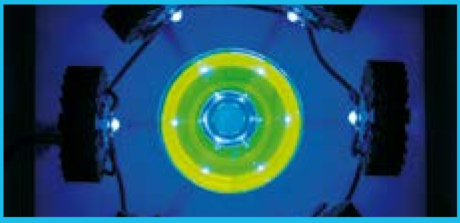
Nanoworld Münster





Nanoworld Münster

Region Münster

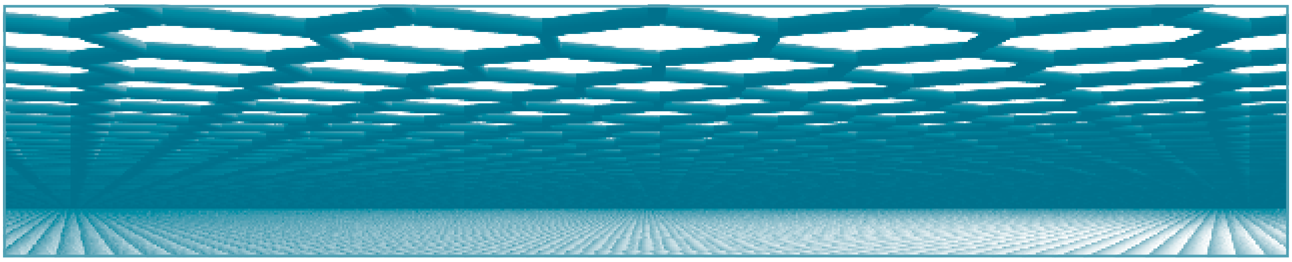
Nanomaterials

Nanobiomedicine

Nanoanalytics and theory

Content

Region Münster



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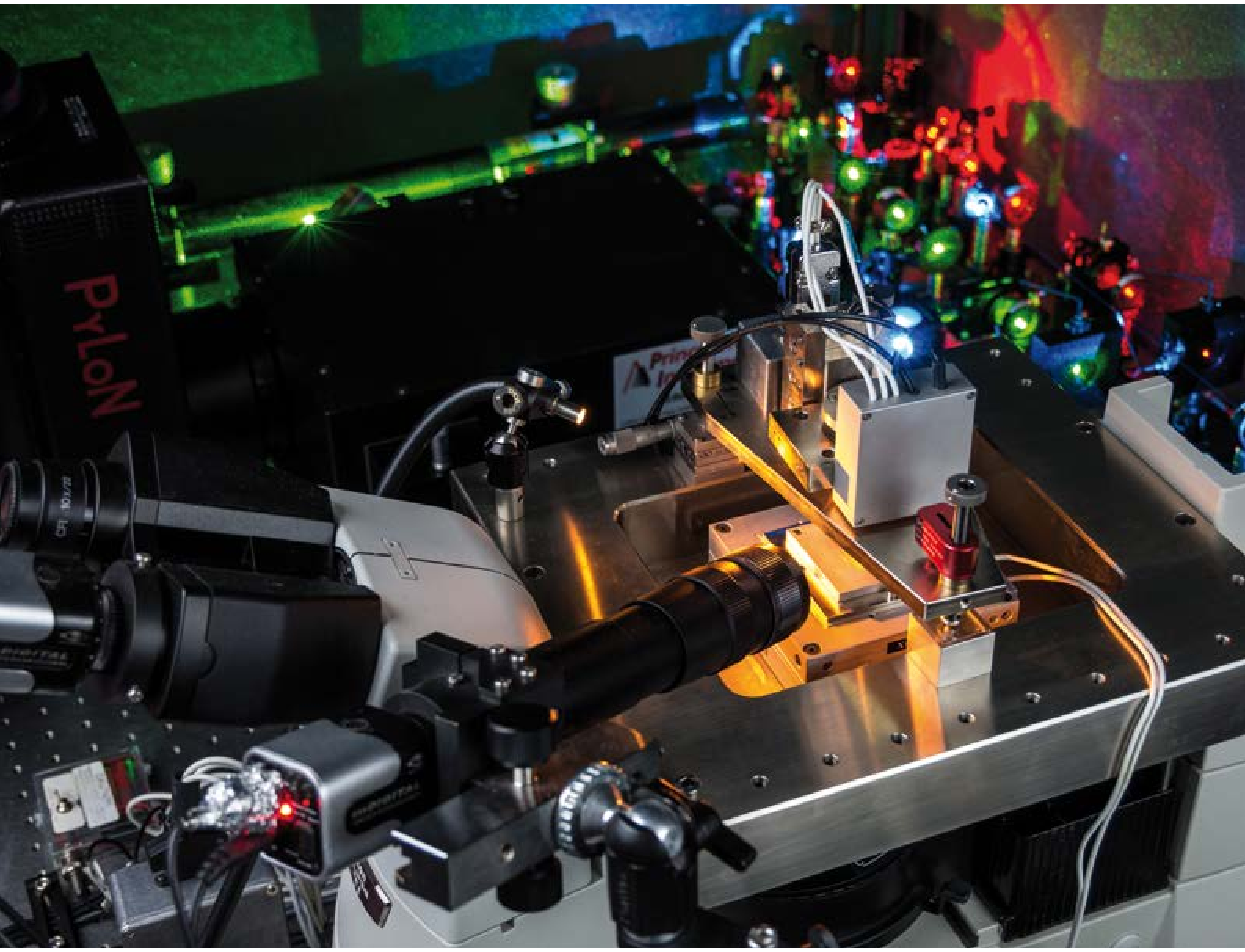


Nanoanalytics and theory

Foreword

Münster has a chance of its population increasing by 30,000 up to the year 2030. There will then be 330,000 people living in our city. This makes us one of the few large cities that can shape for itself a lively future full of diversity.

Münster is undergoing constant change – which is a good thing. Münster has long since become an international city. The future of cities and regions will be either international or nothing at all. An increasing number of people and families from other countries are coming to Münster to live and work here. Münster is a must above all for researchers working in the forward-looking fields of the Life Sciences, Information and Communication Technologies and Nano-technology. Nowadays, in the "nano" field, no one can afford to ignore Münster. And one thing that makes me really proud too is that Münster is the home of the "Cells in Motion" Cluster of Excellence! One thing is absolutely clear: science in Münster is the most important resource of the future – and an elixir for the city.

Not without reason are nine higher education institutions with more than 60,000 students, the University Hospital and other research institutes the largest employers in our city and the most important motor for economic growth. Local and regional companies enjoy above-average growth when they benefit from the research done at the universities. Our city is the campus. That is why one of our biggest challenges in future will be to develop Münster and its universities into a model for sustainability and innovation. Science belongs to Münster's portfolio just as much as the Hall of Peace or the Kreativkai.

Acting closely together in a strategic cooperation that works out-standingly well, the players representing the academic world, business and the city have succeeded in creating lighthouse projects such as the Nanobioanalytics-Centre and turning Münster into a leading site in Europe for education, science, research and development. The importance of the Alliance for Science for our city cannot be overstated.

What this brochure makes impressively clear is that Münster is a dynamic site for nanotechnology. As an ambassador for Science City Münster, I hope the brochure reaches as many people as possible!

Sincerely

Markus Lewe
Mayor of the City of Münster

Dear Readers,

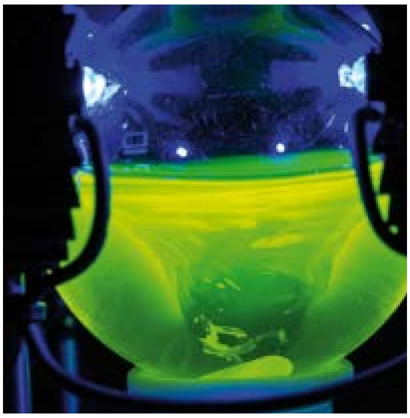
“Vague but exciting ...” – This was the comment of Tim Berners-Lee’s boss when Berners-Lee submitted a proposal to him in March 1989 for the exchange and management of information and data to increase the efficiency at the research location where they were both working, CERN. These three words of approval, scribbled at the top of the paper, allowed Berners-Lee to continue working on his idea, which later was to form the basis of the World Wide Web.

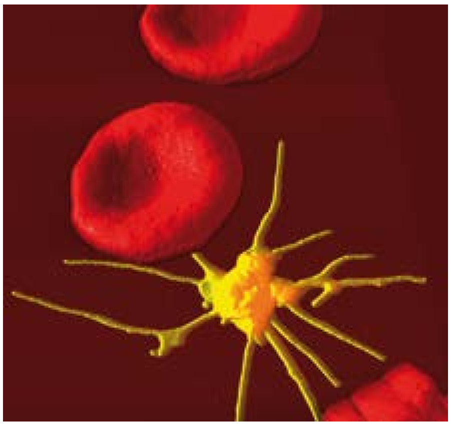
The WWW is one of the most famous “by-products” of basic research. Only when researchers are given the freedom they need to carry out their research unhindered can such revolutionary ideas arise – in both basic and applied research. The nanosciences in particular provide living evidence of this. Münster is an important research location and has not just started following a trend in this field overnight, but has been actively undertaking research in this area for decades. It therefore comes as no surprise that Münster has evolved into one of the leading sites, far beyond the borders of Germany, and it will build on this reputation in future. Numerous examples of cooperation with the city of Münster, Münster University of Applied Sciences or international partners, as well as a regular transfer of technology to business – and all supported by the work done by outstanding researchers – are testimony to the enormous success of research in nanoscience here.

I do hope you enjoy reading this brochure and discovering all the many opportunities which are developing in, with and through nanotechnology.

Sincerely,

Prof. Dr. Johannes Wessels
Rector of the University of Münster





To be able to examine material on a molecular and atomic scale and systematically change it is an old dream of scientists. In nanotechnology, this dream is beginning to come true. It opens up undreamt-of opportunities to create materials with completely new types of properties in almost all fields of technology. Surface finishing, intelligent nanoscale materials, faster electronics, optics, sensors and nanomotors are just a few examples of the uses to which this rapidly growing cross-section technology can be put.

Since 1998, the University of Münster, Münster University of Applied Sciences, the City of Münster and the State of North Rhine-Westphalia have been working closely together to help nanosciences in Münster achieve international visibility.

Some fruits which this strategy has borne – visible far beyond Münster itself – are the Center for Nanotechnology (CeNTech), the Nano-Biocentre (NBZ) and the new Center for Soft Nanoscience (SoN). In addition to numerous instances of cooperation with partners both at home and abroad, the Transregio Collaborative Research Centre TRR 61 is an outstanding example of a successful international partnership of many years' standing. Out of this partnership have arisen further projects with other leading scientific sites in China.

Activities in Münster have paved the way for many European projects and networks, including "Nano2Life" and "Frontiers", as well as for numerous collaborations with industry, which have been successfully put into practice. As a result, at a European level Münster has evolved into an internationally visible hub for nanotechnology. Top-class researchers are appointed to positions in Münster, where they discover a unique research environment in our centres and at Münster University, and they are new ambassadors for both our research and the City of Münster all over the world.

This brochure contains a selection of examples showing the wide range of activities in the field of nanotechnology in Münster.

Sincerely,

Prof. Dr. Harald Fuchs
Scientific Director of the Center for Nanotechnology (CeNTech)
Director of the Institute of Physics of the University of Münster

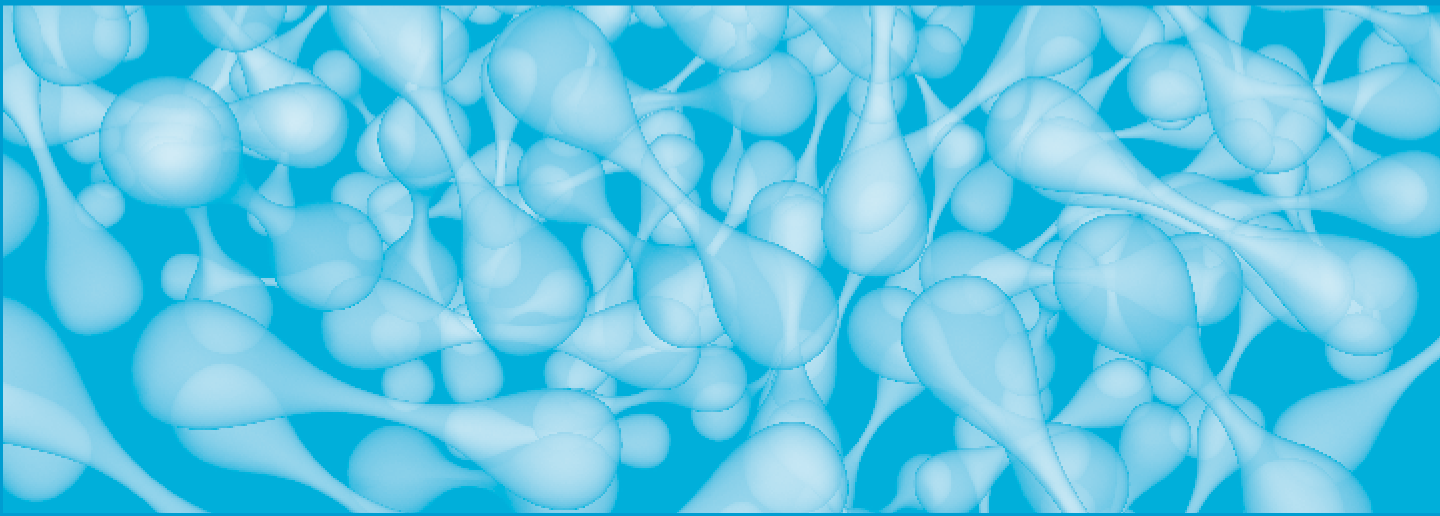
A strong region

The success story of nanosciences in Münster began in 1993. Since then, to strengthen the nanosciences, appointments of new professors have been agreed on within the Department of Natural Sciences at Münster University. The starting point was a long-standing tradition in the development of methods in physics which were suitable for analytical work in the nanometre range and below. With the aid of this, a focus of research arose which was visible worldwide. In 2000 the University, the City of Münster and the State of North Rhine-Westphalia set up a special non-university research centre, CeNTech, whose modern new building was opened in 2003. On one-third of its space, CeNTech houses young start-up companies, making available to them offices, laboratories and technology. In 2012 an expansion of CeNTech had already become necessary – CeNTech II – because the many groups of researchers who had become established there, as well as six groups of junior researchers (five of which had their own financing), needed additional rooms and equipment.

Today CeNTech still retains its exemplary character as an institution run jointly by the City of Münster Business Development Department and the University of Münster – and it has not only preserved this, but has also expanded it. Physicists, chemists, biologists and medical physicists work together here to transform the results of their basic research into practicable concepts as fast as possible. CeNTech GmbH, the holding organization, supports the transfer of technology, for example in the form of seminars, conferences and licensing. The building is very well equipped for this. Collaboration between the University and the City of Münster Business Development Department has also been intensified through CeNTech.

In 2013, the Münster Nanobioanalytics Centre (NBZ) followed with its own new building, where small and medium-sized enterprises undertake research and develop innovative equipment for nanobioanalytics.

In 2017, the new building for the Center for Soft Nanoscience (SoN) will be completed, at which researchers from a variety of disciplines examine the fundamental processes in the production of biomimetic functional materials.



This public-private partnership has not only resulted in a large number of collaborations with industry, both in Germany and at a European level, but has also helped to attract a number of excellent young researchers to Münster. This concept has been confirmed by an above-average number of awards, a high level of third party funding acquired, and numerous appointments to professorships.

Detailed discussions have been intensified with the various decision-makers in the 'Alliance for Science' initiative for the promotion of advanced technologies. Short communication paths and a tight network between City and University make it possible to jointly and efficiently develop a strategy for future areas of technology. A standing Planning and Strategy Committee, composed of representatives of the City of Münster, Münster University research and Münster University of Applied Sciences, allows a close exchange of information, as well as joint planning – for example, in nano-bioanalytics. Goals are implemented in close cooperation with the Business Development Department.

The close proximity to the University Hospital, the Centre for the Molecular Biology of Inflammations and the Max Planck Institute of Molecular Biomedicine allows very close collaboration with many research groups at CeNTech and at the University. Research into phenomena going beyond this, such as hierarchical pattern formation, is carried out together with the Centre of Non-Linear Sciences (CENOS). However, the transfer of technology is not purely a scientific task: it also needs efficient marketing. This activity is covered outstandingly well by the Institute of Business-to-Business Marketing. Intercultural questions relating to research collaboration are handled by the Institute of Business Administration, and ethical issues by the Department of Philosophy at the University. The overall result is an excellent network, which functions supremely well and provides knowledgeable answers to complex problems relating not only to technology transfer, but also to social issues.

CeNTech: A centre with an international reputation

Scientists in Münster are treading new paths to use the many opportunities offered by nanotechnology research

Embedded in a tight network of universities and research institutes, CeNTech offers research groups from the fields of physics, chemistry, biology and medicine, as well as young companies, ideal conditions for a quick transfer of scientific results into new products and applications. The focuses are on the optimization of scanning probe and microscopy techniques, new materials with nanoscale structures, the development of nanoparticles and nanocontainers for biomedical applications and research into biophysical effects, in particular of processes within and between cells. The research building, opened in 2003, has 2,400 square metres of floor space and is home to special laboratories and offices, which meet the specific requirements of nanotechnology. These include, for example, vibration-free foundations, cleanrooms and a comprehensive inventory of equipment. Since late 2011, a further 1,300 square metres of useable space has been available in the CeNTech II extension building, which was financed through regional state and federal funding. Münster University also contributed 2.2 million euros towards the building and the equipment.

Much more than just a special lab

However, CeNTech is much more than just a special laboratory. It is where researchers and business meet. This combination of scientific excellence and entrepreneurial thinking speeds up any transfer into marketable applications. CeNTech GmbH is the holding company for the Centre, and its job is to create an effective platform for exchanges between scientists and partners in business. It not only makes rooms available to companies from the fields of nanotechnology, surface finishing and nanobiotechnology, but also strengthens commercial collaborations. In their first few years, spin-offs are given support, including technical expertise. CeNTech GmbH is also involved in applying for and utilizing patents emanating from the University of Münster. Since the Centre was established, over 20 patents have been applied for. Subsequent licensing

Left: The CeNTech I Centre for Nanotechnology in Münster
Top right: CeNTech II

and sales of patents to industry show clearly the interest that exists.

Nanobioanalytics: a field for the future

CeNTech GmbH is a subsidiary of Technologieförderung Münster GmbH and, as an active member of the Alliance for Science, it is heavily involved in the development of the local region. Nanobioanalytics in particular is seen as one of three fields for the future in the Münster Science Region and has been subject to systematic expansion for some years now. Contributing to this are not only the CeNTech extension, which is used exclusively by the University's nanoscientists, but also the new Nano-Bioanalytics Centre (NBZ), which facilitates the setting-up of small and medium-sized companies.

CeNTech GmbH also undertakes assignments in site marketing. In 2014, NanoBio Europe – the leading trade fair of its kind in Europe – was held in Münster for the fourth time. The primary focus of the event, in which more than 250 representatives from science and business took part, is on medical applications of nanotechnology.

Competence: word gets around

Taking part in marketing projects, by means of which the German Ministry of Research promotes nanotechnologies, is something that supports the process of building up such a profile. Competence from Münster has also been presented for example at the big international conferences and trade fairs in Tokyo, Moscow, Beijing, Boston and Chicago.

In addition, CeNTech GmbH supports all efforts to pursue national and international networking of nanoresearch undertaken in Münster. This includes EU projects such as Nano2Life, Frontiers or Nano4Market, as well as membership of the German Nano Association and the "Nano in Germany" initiative. CeNTech GmbH is also one of the initiators of the German Nanoregions Working Group.

The holding company's competence is paying dividends. In 2012 for example, the Ministry of Innovation for the State of North Rhine-Westphalia once again commissioned CeNTech GmbH, as leader of the consortium, to run the Technology Cluster "NanoMikroWerkstoffePhotonik.NRW".

In this context, CeNTech GmbH also took on the management of the COPT.NRW project, which is about creating an environment conducive to innovation in the state of North Rhine-Westphalia in order to strengthen science and business, as well as to raise the state's profile both at home and abroad. The close collaboration undertaken by all those involved in technology transfer provides fresh momentum for the region.


Dr. Holger Winter


Dr. Thomas Robbers

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"A unique mix of depth and diversity"

The Münster Nanoregion is a model of fruitful cooperation. Links with China are particularly close. In this interview, Prof. Dr. Lifeng Chi and Prof. Dr. Harald Fuchs reveal the strategy which led to this success – and how dogged determination pays off.

What is the impetus that Münster provides?

Prof. Dr. Harald Fuchs: The Münster Nanoregion has developed enormously over the past few years. The focus was initially on nanoanalytics. Entire professorships were engaged in developing new methods and equipment in order to delve ever deeper into the secrets of the hidden world of atoms and molecules. There is a universe of its own lurking there, and researching into it constantly brings forth new and exciting discoveries. For the most part, it is quantum mechanics effects, as well as special chemical ones, that we want to explore. What needs to be done now is to use the findings for new applications and products. In the past few years, the groups working in the field of nanoanalytics have been extended by a similar number of researchers engaged in nano(bio)materials. This means that today more than twenty university chairs in Münster – spread over the natural sciences and medicine – have links with the "nano" field.

Prof. Dr. Lifeng Chi: Nanoanalytics is very strong in Münster, and word about that has got around as far as China. Many researchers in the fields of physics, chemistry, biology and medicine are well networked and work very effectively together. Earlier, nanomaterials were not yet as strongly represented as they are today. Research into self-organization is a strong area of research in Münster, which links up very well with groups engaged in work with a biological orientation or in non-linear physics.

Prof. Dr. Harald Fuchs: These new topics not only need excellent equipment for conducting experiments, but also outstanding theoreticians who can interpret the results gained from these experiments. That is another advantage of the Münster nanoregion.

How do you organize the collaboration between so many groups and players?

Prof. Dr. Harald Fuchs: At an early stage, over 15 years ago, we set up a competence centre of the Federal Ministry of Research, which evolved some years later into the Centre for Nanotechnology CeNTech. It represents close collaboration between the University and the city and is unique in this form, exemplary. At CeNTech, University researchers and companies work together under one roof, which is an especially stimulating and fruitful environment. In this way, we can quickly transfer the results from basic research to new processes or products for industry. It means we are also able to further develop our unique basis in equipment in collaboration with those colleagues who are more materials-oriented. So far, we have eight start-up companies at CeNTech, and a lot more companies have set up business nearby. Patent utilization is handled by CeNTech GmbH, especially set up for the purpose. Many years of work spent on building things up are now bearing fruit.

Is CeNTech the core of the nanoregion?

Prof. Dr. Harald Fuchs: It certainly is! This centre represents the successful creation of a new structure between the city and the University of Münster. The city had the aim of bringing as many high-tech jobs as possible to Münster, and the University needed capacity for interdisciplinary research. If the state of North Rhine-Westphalia, the city of Münster and Münster University had not pulled together so well, we would hardly have made the progress that we have. We have always had the full support of both the former mayor and the current mayor for our project. That this collaboration has been a fruitful one is shown not only by the many patent applications we have made and the numerous scientific awards we have received, but also by the CeNTech extension that was completed in early 2012 – because the CeNTech building we had up to then had become too small after just a few years of working there.

How many researchers are actively involved in nanotechnology in and around Münster?

Prof. Dr. Lifeng Chi: In CeNTech alone there are around 100. In the whole region, there are probably anything up to 300. I am talking here about highly qualified jobs in research and development. In the companies, the number is likely to be a few hundred.

Contacts between Münster and various universities in China are particularly close. How do you manage to carry out joint research and teaching across the continents?

Prof. Dr. Lifeng Chi: We began the first projects in the mid-90s, mostly in the form of personal contacts between professors. At the end of the 90s, nanotechnology took an enormous leap forward and, as a result, there was a big increase in worldwide networking between groups of researchers. At the beginning of this millennium, the state of North Rhine-Westphalia began to fund our Chinese projects, for five years. We had the first transcontinental Collaborative Research Centre in Münster – the Transregio 61 (TRR 61), which the German Research Foundation had set up. The German Research Foundation and its counterpart in China, the National Science Foundation of China (NSFC), funded the TRR 61.

Prof. Dr. Harald Fuchs: When I got my PhD in nanotechnology in 1982, there were only two or three research groups in the whole of Germany who were working in this field. I have been in Münster since 1993, and at that time we were already beginning with exchanges of PhD students and postdocs to China.

How does the collaboration work today?

Prof. Dr. Harald Fuchs: Science is pursued first and foremost by dedicated people. That is why exchanges of researchers is a top priority – and not, incidentally, only to China. We have close ties for example with India, the United States, Japan, Singapore, Brazil, Cuba, Korea and Argentina. We routinely hold videoconferences in our lectures, seminars and meetings, for example with universities in South Korea, Brazil and China.

Prof. Dr. Lifeng Chi: I am a professor here at Münster and, at the same time, at Soochow University in Suzhou. I have a team of researchers both here and there. In my group here, there are six PhD students and postdocs. In Suzhou, I now have around 20 students, postdocs and staff. Around two dozen researchers take part in regular exchanges between the German and the Chinese groups.

In other words, you spend six months in Germany and the other six in Asia ...

Prof. Dr. Lifeng Chi: We even go so far as to hold videoconferences with Chinese colleagues to discuss how certain measuring results from Chinese material samples should be evaluated here in Münster. The physical distance is then irrelevant. We use video-technology to organize joint seminars for the research groups. So overall I spend about six months a year in China, and the other six I live and work here in Münster.

Prof. Dr. Harald Fuchs: I travel to China for short stays about two or three times a year. We also have a different kind of "mobility" thanks to modern technology. What is important first of all is personal contact. After that, a lot can be done via modern media and the Internet. Six or eight times a year, I travel to international congresses or to our partner universities to work with the students there. Of course, I always like coming back home to Münster – not only because of the outstanding scientific environment, but also because life is so very pleasant here.

Interview conducted by Heiko Schwarzburger.

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TRR 61: A pilot project sets an example

The transfer of knowledge is not a one-way street – as is demonstrated by a pioneering project involving collaboration between Chinese and German researchers

Building on several years of exchanges between Münster and Chinese universities, involving researchers from the fields of nanophysics and nanochemistry, Professor Harald Fuchs, Professor Lifeng Chi and Professor Xi Zhang have succeeded in putting this successful collaboration on a longer-term basis. In 2008, the German Research Foundation and its Chinese counterpart, the National Natural Science Foundation of China (NSFC), decided to provide financial support for the joint research being carried out. The researchers want to systematically study the properties of molecular assemblies.

In the first transcontinental German-Chinese Collaborative Research Centre "Multilevel Molecular Assemblies: Structure, Dynamics and Functions" (Transregio 61, TRR 61), over 90 researchers are working in 24 projects. On the German side, the German Research Foundation is providing around 16 million euros up to 2020. At the same time, the Chinese researchers are being funded by the NSFC.

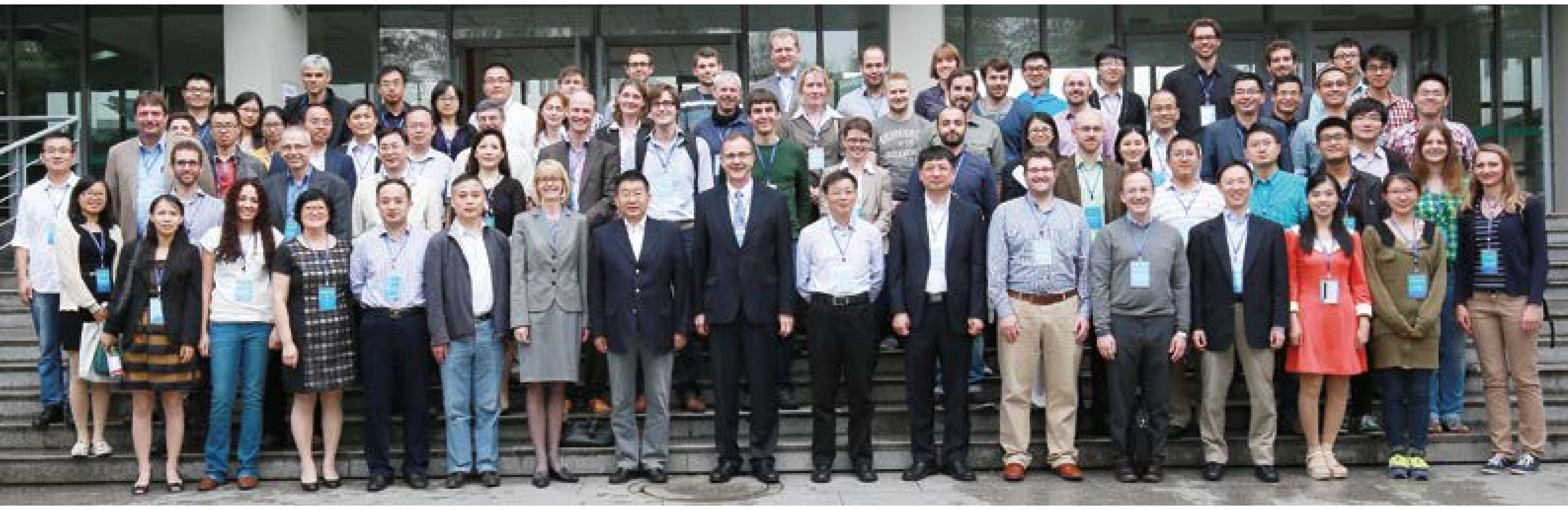
Pooling expertise

Physicists, chemists and biologists from prestigious teams in China and Münster pool their expertise when undertaking research into unsolved problems of molecular assemblies as well as into their great technological potential. The first project phase focused on fundamental mechanisms of molecular systems, especially multiple interaction, cooperative effects and dynamic behaviour in self-organization in molecules. Phase two concentrated on the controlling properties which proceed from self-organizing molecular systems and which display extended functionalities, especially in molecular electronics and other responsive molecular systems.

The longer-term aim which the researchers have is to understand and control the properties and functions of molecular assemblies. They produce molecular materials with tailor-made electronic, optical and sensory properties, which fulfil certain functions thanks to their structure and their collective behaviour.

Some concrete aims are:

- to improve functional systems by optimizing the charge carrier mobility of molecular transport and optical spectral tuning as regards emission, absorption and polarization, and
- to produce switchable and responsive materials which are able to change shape, electro-optical properties, wettability and binding properties through external stimuli; and to construct bio-hybrid systems for biocompatible surfaces and sensitive biosensors.



Symposium of TRR 61 researchers in Suzhou

Three clusters defined

In order to implement these ideas, three clusters were defined. In Cluster A, the chemical properties of the assemblies are examined in the dissolved phase. Cluster B is devoted to complex assemblies at interfaces and surfaces. Cluster C focuses on bi-ohybrid assemblies. Many of the 24 projects work hand in hand with partners from Beijing. Others are headed by a Chinese or a German researcher. Transregio 61 also offers an intensive exchange programme. Not only the project leaders have an opportunity to visit the partner country. Each of the 50 or so doctoral students can spend up to three months with a cooperation partner to broaden their knowledge and stimulate the transfer of knowledge – in both directions.

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Fascination and encouragement all in one

Through fascinating experiments and laboratory workshops, girls and young female students find current research in the field of nanotechnology attractive

Due to its origins in natural sciences, research in the interdisciplinary field of nanosciences is characterized by the visible underrepresentation of women in the so-called MINT subjects (Mathematics – Informatics – Natural Sciences – Technology). In order to attract excellent female researchers to nanophysics and nanochemistry, it is required to offer systematic support to women right from the start of their studies. This includes, on the one hand, to take steps at the critical transition from school to university to motivate schoolgirls to pursue a degree course in Physics or Chemistry. On the other hand, female students need to be supported in the early stages of their careers through networking and mentoring.

Encouraging young women through science

Nano4YourLife address exactly these issues. It is a project within the Transregio TRR61 Collaborative Research Centre under the direction of the MExLab Physics (Münster's Experimental Physics Laboratory), aimed at schoolgirls aged 16 to 18, as well as at female students of Physics and Chemistry up to their second semester. The primary goal is to use exciting experiments to demonstrate the participants the highly modern and fascinating combination of Physics, Chemistry and Biology that nanosciences offer – and thus awaken their interest in natural sciences. At the same time, they get to meet other girls, with whom they can build new friendships. After all, the one thing that all 'NanoGirls' have in common is curiosity in the natural sciences. Through direct contact with scientists from the fields of Physics, Chemistry and Biology, Nano4YourLife automatically provides guidance on choosing a degree course and a later career. This is done in the form of three projects.

In the first project, which entails two big one-day workshops, all participants carry out research relating to unique nano-effects, fascinating nanomaterials, and nanotechnologies of the future. In the first of these workshops, and under the motto "Insight into Nanosciences", participants work on their own, using a wide range of materials to do experiments related to the lotus effect. The dream of eternal purity is one example from the field of impressive nano-surface effects, and one which astonishes observers: Why do kohlrabi and tulip leaves always stay clean if the surface of the leaf is untouched – but lettuce leaves do not. Aside, experimental stations with ferrofluids offer insights into the extraordinary, fascinating properties of magnetic fluids. A fluid that flows upwards, barbed structures, coins that float within as if by magic – all these phenomena, typical of the field of nanoparticles, delight the participants.

The second workshop is entitled "OLEDs – Learning from Nature how to Shine". The NanoGirls learn about phosphorescence in painting mobile phone holders with colours that shine in the night, and are delighted at the subsequent experiments showing the fluorescence of tree sap from horse chestnut trees. Who would have thought how impressively the sap shines in water under ultraviolet light? These two examples of photoluminescence are just the beginning. Chemiluminescence – shining due to a chemical reaction – gets the girls reaching for their smartphones to take photos for family and friends. After that, it is only a small step to the illustration of electroluminescence, in which light is emitted due to electric current. This phenomenon represents the basis for the way organic LEDs (or OLEDs) function.

Layers with a density of just a few nanometres characterize the structure of these lamps of the future. During the workshop, the NanoGirls construct simple variants of the OLEDs and, in the process, become familiar quite naturally with Physics and Chemistry. There are presentations of sub-projects within the Collaborative Research Centre at the University of Münster – including topics such as nanosurface effects, particles and layers – while in the big workshops these presentations serve as link to the research activities being carried out in the nanosciences.

The so-called NanoGirls@Work Events, which last one day, allow the participants to go into more detail with their own interests. From among a wide range of events, the NanoGirls select two. Girls carry out experiments and research in small groups on a narrowly defined topic. Later, they perform real experiments belonging to research projects or studies being currently undertaken in laboratories, research institutes or companies they visit. Instead of having a traditional guided tour, this way of getting to know research and industry enables the participants to understand complex research and operate high-tech equipment, thus interactively discover new jobs and occupations.

The third project is an online forum for networking among the NanoGirls. This one is particularly interesting for them due to the heterogeneity of the schoolgirls and students. Because of this mixture, it automatically offers guidance on degree courses and future careers. Nano4YourLife represents thus a perfect symbiosis of topics related to the nanosciences, the experience of interdisciplinary exchanges, and the encouragement for young women through role models.

Symbiosis between fun and research

Nano4YourLife is already seen as a success by the girls taking part of it. This fact is in turn reflected in the high numbers of registrations and the regular participation by the NanoGirls: 57 schoolgirls and female students enrolled in Nano4YourLife since May 2014. Numerous @Work Events are still to be held before the project ends, all of them supported by researchers from the Transregio TRR 61 Collaborative Research Centre and the Centre for Nanotechnology (CeNTech).

The students who are taking part of it – now in their fourth semester – are busy making first contacts so that they can undertake their bachelor theses in the laboratories of the Collaborative Research Centre. Chatting with the students, the schoolgirls get feedback on relevant degree courses perfectly tailored to each one's wishes and plans.

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Münster: a nanobioanalytics region

Today, Münster is a heavyweight in European nanobiotechnology – but it needed perseverance

Using new high-resolution chemical and physical analytical methods to examine cell biology processes, as well as their reaction to chemical stimuli or materials, opens up new opportunities for research into the causes of and treatments for diseases, for a sensitive detection of contamination of food or the environment, and for testing the safety of consumer products.

More than four decades of experience

In the Münster region, the scientific basis necessary for such analyses is excellent. It has a long tradition covering a wide range of high-resolution nano-analytical methods, and is coupled with outstanding biomedical research. It started about 40 years ago with decisive developments in electron microscopy made by Prof. Dr. Pfefferkorn, followed by pioneering research results in the field of mass spectrometry with Prof. Dr. Hillenkamp as one of the inventors of MALDI technology. The same is true for Prof. Dr. Benninghoven in the field of TOF-SIMS mass spectrometry. The analytical potential built up is completed by the near-field probes developed by Prof. Dr. Fuchs and the largest university group working in the area of analytical chemistry, under Prof. Dr. Karst.

This analytical work, fed primarily with input from the Institutes of Physics and Chemistry at Münster University, has become increasingly networked over the last few years with biomedical knowledge in the Faculties of Medicine and Pharmacy, as well as with Münster University Hospital. Especially worthy of mention here are the Max Planck Institute of Molecular Biomedicine, with one of the world's leading teams in the field of stem cell research, led by Prof. Dr. Schöler, the Centre for the Molecular Biology of Inflammations (ZMBE), and the European Institute of Molecular Imaging (EIMI). The current highlights of this ever more intensive networking are the "Cells in Motion" Cluster of Excellence and the Centre for Soft Nanoscience (SoN), where analytical work on cells and their interaction with new nanomaterials continues to be pushed forward. The ability to develop new materials on the nanometre scale and to examine in detail their interaction with cells and tissue is an essential condition for understanding how diseases arise and for developing new treatments based on nanomaterials.

Close contacts to business

The interdisciplinary nature of the research environment is fertile ground, and increasingly so, for the commercial use of research results. Over the last few years, more than 30 companies have been set up in the region, not only developing analytical equipment and testing systems, but also offering analytical and biotechnological services. These include spin-offs such as ION-TOF GmbH, the world leader in the field of TOF-SIMS mass spectrometry; or Wessling GmbH, which provides analytical services for food and the environment.

Intensive networking has also been established among companies, with the best example being the setting up of the Münster Nano Characterization Lab (www.ncl-muenster.de). This consortium, comprising eleven companies and the Biomedical Technology Centre at the Faculty of Medicine, provides support for customers in the food, cosmetics, pharmaceuticals and environmental industries in characterizing the nanocomponents in their products, thus making an important contribution to the safety of these products.

New centres improve the infrastructure

This networking between science and business is supported by new centres such as the Centre for Nanotechnology (CeNTech), in which, in particular, applied research and its practical implementation take place in spin-offs, or by the Münster Nanobioanalytics Centre (NBZ), in which small and medium-sized enterprises have an excellent environment for nanobioanalytical innovations. The short distance to the SoN, Max Planck Institute, Münster University Hospital and the building being planned for CiM will ensure continuous exchanges in the future, too.

Front view of the new Nanobioanalytics Centre in Münster

Breathing life into the network

Every regional network needs a driver and a communication platform. Both were set up 13 years ago in the form of the Gesellschaft für Bioanalytik Münster e.V. Since then, scientists, companies and local representatives of the region have been using this platform to develop joint projects and maintain networks with external partners and regions.

Thus, Bioanalytik Münster represents the Münster region in the European Nanomedicine Technology platform and ensures that the region's potential in terms of nanobioanalytics finds its way into projects with European partners such as the European Nanomedicine Characterisation Laboratory (www.euncl.eu). Bioanalytik Münster is also one of the main players in the state of North Rhine-Westphalia's "NanoMicroMaterialsPhotonics" Cluster, which promotes and organizes nanotechnology in the state on behalf of the state government.

A unique feature of Münster as a region for nanobioanalytics is the Alliance for Science, which comprises the University of Münster, Münster University of Applied Sciences, and the city of Münster. Together, their aim is to push forward further strategic development of the interaction between science, business and the Münster region.

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A major part of everyday life

After almost 60 years, Richard Feynman's vision becomes reality: nanotechnology has enormous, untapped potential

55 years after Feynman's talk, nanotechnology is an integral part of modern everyday life, which has long since contained examples of nano-based applications. Nanomaterials can be found in cosmetics, on food packaging, in lithium-ion batteries, in paints and varnishes, in cancer treatment, in LEDs and in electronic devices. The coming years will be marked even more strongly by rapid developments in this still-young science. In addition, an increasing number of innovative applications will follow. Nanotechnology's motto is "smaller, faster, and more efficient". In economically important branches of industry such as chemicals, electronics, medicine and energy, the nanosciences make an important contribution to competitiveness, making possible innovative processes and products, which save on resources. According to a study published by the German Ministry of Research in 2015, the overall market for nanomaterials is estimated to be worth around 20 billion dollars.

In 2014, the market for nanotechnology tools was estimated to be worth 90 billion dollars. In the field of medicine, analysts at BCC Research expected turnover alone in the global health sector to reach more than 96 billion dollars in 2016. Nanomedicine is seen as being especially promising in the treatment of tumours. In energy generation, thin-film solar technology promises great potential for growth, and this market could soon be worth 820 million dollars, achieving annual growth rates of around 40 per cent.

90 billion dollars

Similar figures are expected in energy storage, likewise a part of nanotechnology. This potential was recognized early on by the government and by business. Advances into the dimensions of nanoparticles and into the space between atoms and molecules occur because of research into the physical and chemical basics. Developing products and launching them onto markets thus go hand in hand.

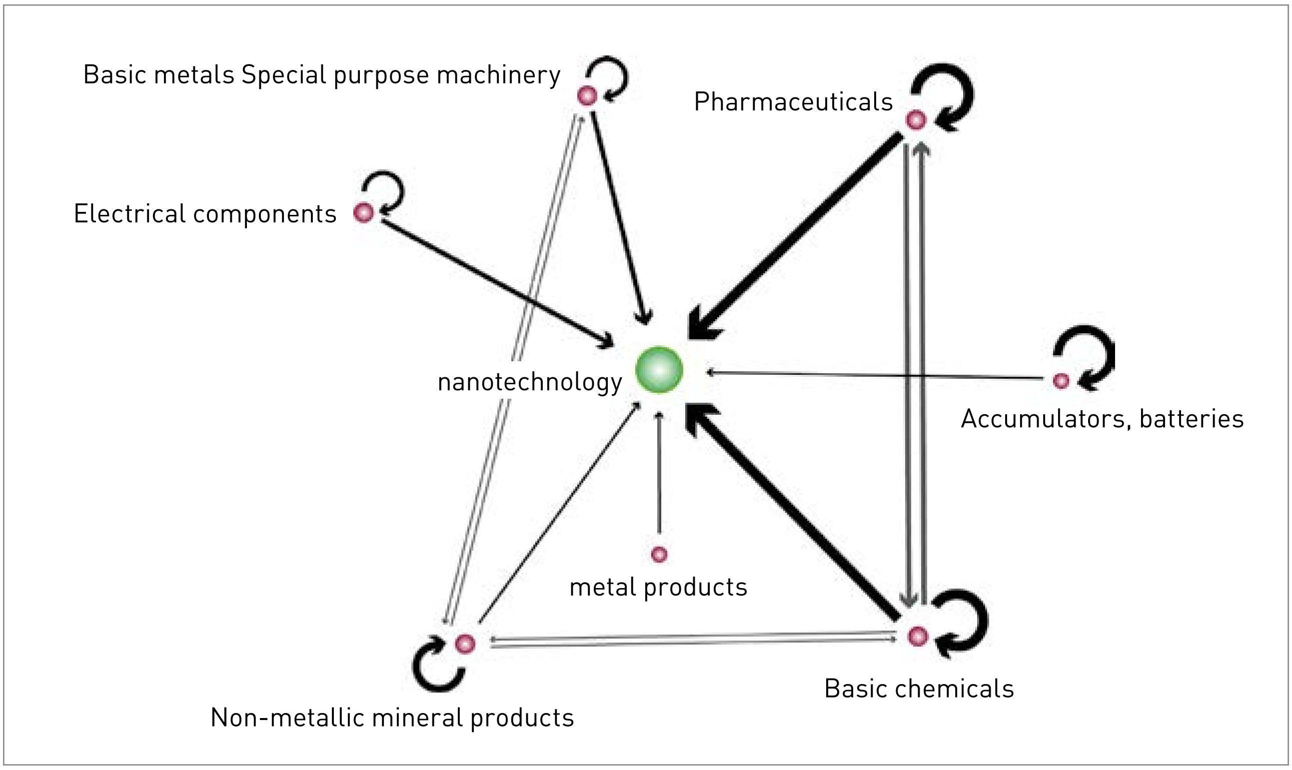

Illustration of technological fields, based on patents, which have links to nanotechnology

From 2010 onwards, university research institutes received annual public funding amounting to more than 400 million euros. Leading chemical companies such as BASF, Bayer or Evonik invest hundreds of millions of euros in nanotechnology research and development – according to OECD figures, BASF alone has invested around 300 million euros. The competence centres for nanoanalytics in Münster, nano-optics in Berlin, nanochemistry and nanobiology in Saarbrücken, nanomaterials in Stuttgart and the nanobiotechnology network in Munich are all seen as examples of successful collaboration between universities and companies.

Innovation needs management

Comparatively long research and development phases are needed to create nanotechnology innovations, which, as marketable products or processes, can revolutionize entire branches of industry. It is very difficult to plan the transition from basic research to an application. It is not always clear how long this process will last – or even whether it will be successful at all. This phase needs time, work and capital, and it generates hardly any income.

In order to make commercial use of nanotechnology's potential, an efficient management of innovations is indispensable. The task of such management is to support new ideas from basic research to market launch – taking in applied research, development and production along the way. The important thing is to plan and monitor the innovation process using commercial criteria, and to identify the most important indicators for measuring and evaluating performance. The main objective that innovation management has is to take the "magic triangle" of work, time and result and, out of these, achieve measurable advantages over competitors.

A common language

Nanotechnology has many facets, bringing together many different fields of knowledge. It is for this reason that cooperation between researchers and companies, as well as between customers, suppliers and competitors, plays such an important role. Cooperation allows partners to integrate knowledge from outside, to share resources and risks, to shorten development processes or to gain access to markets. For two-thirds of German companies working in the field of nanotechnology, cooperation with European partners plays a significant role, while around one-third see collaboration with partners in North America and Asia as being important.

Any cooperation always entails higher transaction costs, an increase in complexity and the risk of an outflow of critical knowledge. Here, too, innovation management can intervene to coordinate and monitor. If nano-researchers and managers find a common language, the development of innovative products and processes will be successful, making nanotechnology a key to growth.

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From invention to innovation

Nanotechnology researchers in Münster do not confine themselves just to inventions – they also look for ways into the market in order to turn their inventions into innovations

Nanotechnology is a cross-sectional technology and is one of the most important drivers for innovation in many areas of life. These include medicine and biology, consumer electronics and automation technology, mobile communication devices, computers, sensors or automotive coatings

Nanotechnology researchers are at home in interdisciplinary communication. Nevertheless, in practice it can often be seen that they are still not sufficiently broad-based. Their success depends not only on being technically superior to other solutions. Disseminating the technology also requires a systematic idea of how to market it.

Innovation: from the basic idea to the product

As easy as it may seem to launch good ideas onto the market, the way there can be very complex and, in some cases, full of pitfalls. In Münster, networked strategies are applied to smooth the way. Several institutes within Münster University and the Technology Park are there to give advice to start-up companies. This includes drawing up business plans and acquiring funding. On the technical side, the Center for Nanotechnology (CeNTech) has its CeNTech GmbH to help nano-companies – not only as a kind of incubator, but also to provide any companies already integrated with technical advice, as well as support in all matters relating to patents and renting space. This range of instruments, as well as the Alliance for Science between the University and the city of Münster, help anyone leaving university and starting up their own company to make that start professional, smooth and successful. This also applies to any external companies setting up business in Münster's nanoworld.

If this is not present, the invention will not find its way into the market and will not become an innovation. Examples of this are legion: the scanner, for example, was invented by the Siemens subsidiary Hell as long ago as 1963. However, it was companies in the Far East and America which transformed this invention into a success on the market.

Although the mp3 player was developed at a Fraunhofer Institute in Germany, it was primarily Japanese companies that successfully marketed it.

Broad collaboration

In other words, the inventors think first and foremost of the technology involved. For the market, however, the new technology has to be translated into benefits. It is here that there is a structural deficit in German technological research.

If we try to illustrate the problem graphically, the result is this: if the two dimensions "technological advantage" and "benefit" are considered, together with the relevant dichotomous characteristics "present/not present", a matrix is produced in which the most frequently occurring case is the quadrant bottom right.

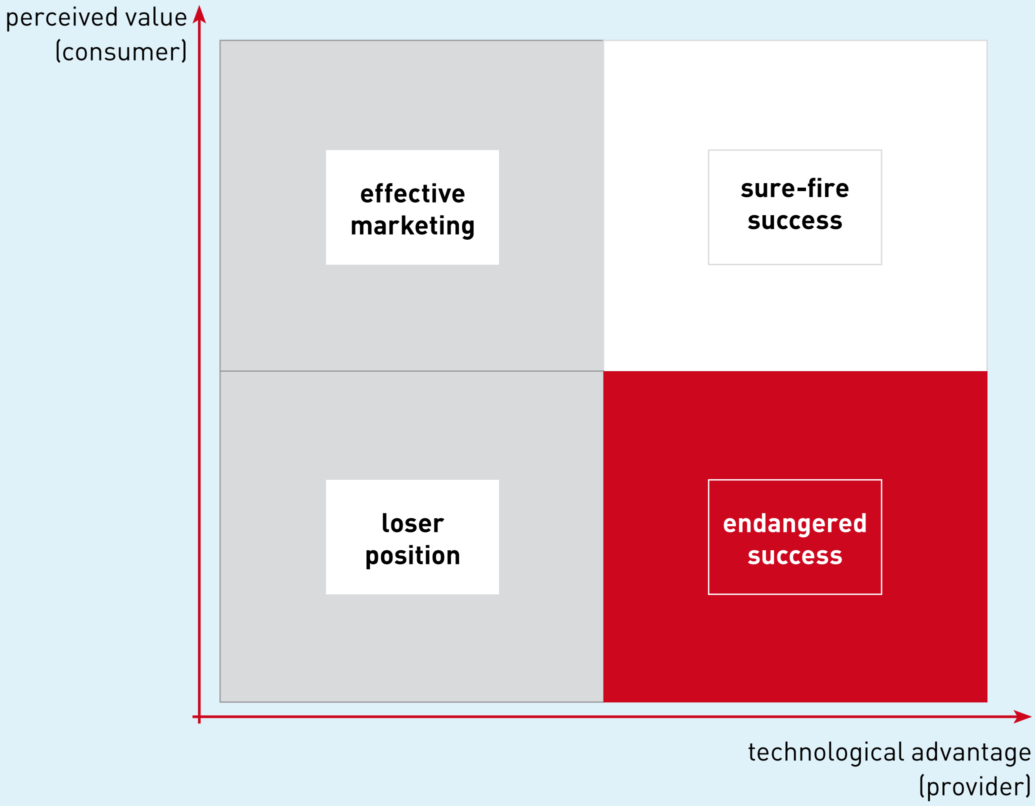
A technological advantage is available which has not yet, however, been translated into a benefit. However, Münster's nanotechnology researchers have recognized how important it is to do this.

Setting up CeNTech meant that research and the practical applications of its results were brought together. First successes were achieved in a collaboration between CeNTech and the Institute of Business-to-Business Marketing (IAS), with the foundations being laid for cellZscope in the Department of Biochemistry at the University of Münster.

An integrated strategy for marketing

Using this new piece of laboratory equipment, cellZscope, an automated in-vitro analysis can be made of certain properties of biological cells. A start-up company at CeNTech, nano-Analytics, developed the equipment from a prototype to a marketable product. Today nano-Analytics produces and sells it all over the world.

As it is a business-to-business product, the obvious thing to do was to ask the specialists from the



Institute of Business-to-Business Marketing (IAS) at the Marketing Center Münster (MCM) to develop an integrated marketing strategy. They began by defining and demarcating the relevant market, as well as analysing the competitive advantages, and then on this basis they identified what had to be done to ensure successful marketing. Specifics were then added, involving recommendations for product policy, communication, pricing and marketing.

Leaving the ivory tower

Prof. Dr. Hans-Joachim Galla, managing director of the Institute of Biochemistry, characterized this interdisciplinary collaboration as follows: "It is impressive to see how interdisciplinary collaboration between different parts of the University can deliver such concrete results."

Nanotechnology in Münster has left the ivory tower of pure technological research. Today it is one of the three scientific fields by means of which Münster aims to raise its profile as a science city. The initiators of this project, Prof. Dr. Harald Fuchs and Prof. Dr. Klaus Backhaus, will continue to extend this collaboration – which will in turn continue to raise the profile of nanotechnology in Münster.

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New home for biomimetic nanosystems

From 2018, twelve teams will be carrying out research together at the Center for Soft Nanoscience

At the Center for Soft Nanoscience, chemists, biophysicists and biochemists, physicians and physicists work on understanding functional natural materials and on the systematic, self-organized structure of synthetic materials with controllable functions. Natural materials, too, organize themselves and are characterized by a wide range of properties, which inert, synthetic materials such as steel or aluminium do not have.

Repairing themselves

Soft materials have a modular structure and the ability to repair themselves if damaged. Of central importance here is the precise and, at the same time, spatially and temporally dynamic arrangement of the individual components. Membranes of biological cells are an example of both the wide range of functions as well as the dynamic arrangement of the individual functional elements.

Control over this natural way of functioning in synthetic, biomimetic nanosystems is set to be a key competence in nanosciences in the future. In the long term, it will permit not only a wide range of innovative approaches but also the targeted release of active substances, as well as the controlled formation of interactive (cell) systems and the production of new kinds of functional materials, thus also helping to save on resources.

The production of biomimetic functional materials will be carried out in line with the molecular bottom-up principle and will initially focus on functionalized, three-dimensional nanomaterials and addressable containers.

The research programme is organized in two interconnected fields of research and one for methodology. In the "synthesis and self-organization" field of research, soft nanomaterials are produced – following the example of nature – from synthetic and natural molecular components (carbohydrates, peptides, lipids, DNA, polymers and so on).

In the "controllable nanomaterials" field of research, nanomaterials are produced which can be controlled spatially and temporally through external stimuli (e.g. light, pH value). Thus, nanocontainers, molecular layers, gels and hybrid materials will be subjected to controlled influence. New kinds of nano-processes will have to be developed for the precise composition of the individual assemblies, as well as for monitoring what has been achieved.

Particularly eligible for funding

In 2013, the German Science Council declared this interdisciplinary research approach to be particularly eligible for funding and, as a result, recommended that a dedicated research centre be built for this purpose. A new, ultramodern research building for the Münster University is therefore being constructed on Busso-Peus-Straße, very close to the

Max Planck Institute of Biomedicine and to the Nano-Bio-Centre. Half of the funding has come from the government in Berlin and half from the state of North Rhine-Westphalia. The building is due to be completed in 2017.

At the Centre, around twelve teams will be using the most modern nanoanalytics processes, from super-resolution optical microscopy and various screening processes to electron microscopy, to examine the systems produced – not only structurally, but also temporally and spatially, using femtosecond lasers. Not only principles of self-organization will be used, but also molecular inks (dip-pen lithography) and nanostructuring processes (electron beam lithography, focused ion beam lithography), among others. Several junior researcher groups and individual projects from other groups are also included in the research programme.

Center for Soft Nanoscience (SoN), Busso-Peus-Strasse 10

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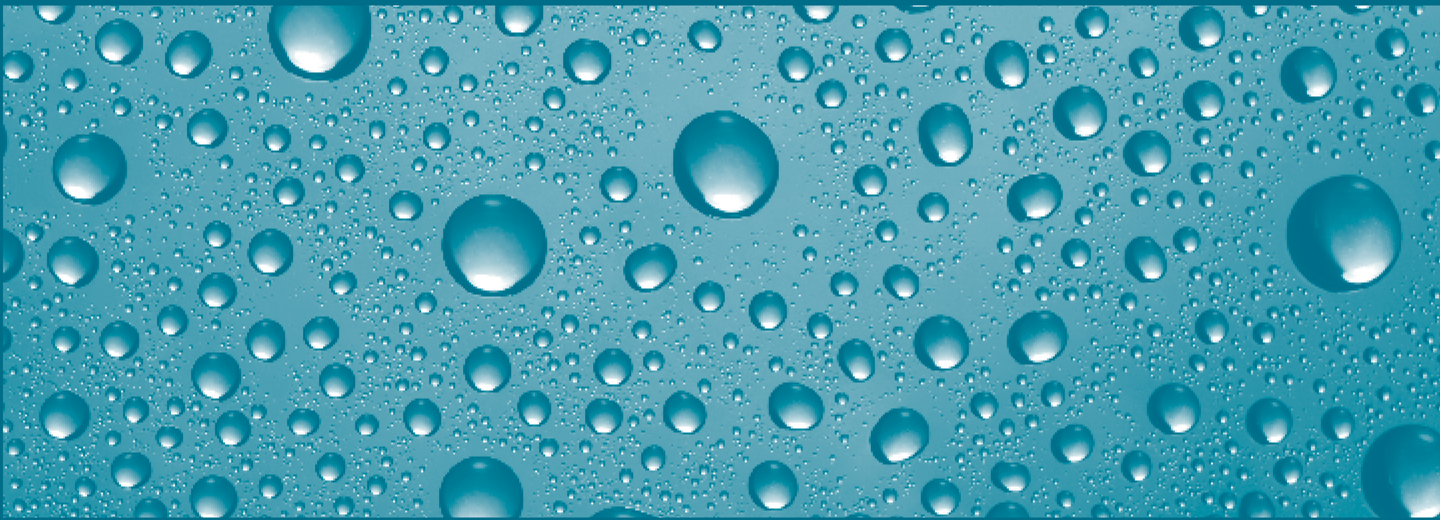
Nanomaterials

Nanomaterials are materials, which – due to their nanoscale, i.e. their size or dimension – have certain physical properties which are not known in macroscopic pieces of these materials. These new-quality properties do not depend on the chemical composition, but are based solely on quantum phenomena. Mostly, these phenomena occur in dimensions of ten nanometres and smaller. They can be used for example to undertake targeted controlling of colour or of catalytic or electronic properties.

If a sample of material of less than 100 nanometres is dissolved, an area is reached in which the laws of quantum mechanics become apparent. At the University of Münster as well as in companies, such small extracts from solid bodies or biomolecular samples are subjected to intensive research and then developed in work being done in the fields of natural sciences and medicine. This produces collaborations in interdisciplinary research teams, Clusters of Excellence and Collaborative Research Centres. Such complex structures are necessary in order to find answers to many different types of questions and to be able to compete internationally.

The development of nanomaterials requires intensive collaboration with teams of researchers working on nanoanalytics and on theoretical aspects. Münster had already made a name for itself internationally in this field before research into nanomaterials was increased. This happened because of the systematic appointment of material researchers from the fields of physics, chemistry and biology, as well as from theoretical medicine and pharmacy.



There are eleven professors working on the development of nanoanalytical methods, and a similar number who are dealing with materials with the most varying characteristics, with inorganic nanosystems, organic stimulatable systems, and biological and nanomedical systems.

One of the catalysts for this process was the FOKUS initiative. This name stands for the interdisciplinary Research Centre for Cooperative Nanoscale Systems – with which, in 2004, the University's management created the opportunity to establish three new professorships in the field of nanomaterial research. They were endowed with full voting rights between conventional departments, for example Physics and Chemistry or Physics and Biology.

In this way, the traditional borderlines between departments were erased, making problem-oriented research work possible. This initiative gave rise to five groups of junior researchers whose work was supported through external funding, among which were grants from the European Research Council and the Alexander von Humboldt Foundation (Sofja Kovalevskaja award). The following pages contain details of some of the research projects relating to nanomaterials being undertaken in Münster.

Nanophysics meets chemistry

Chemical reactions on nanostructured surfaces open up entirely new synthesis processes for producing molecular structures and functionalities

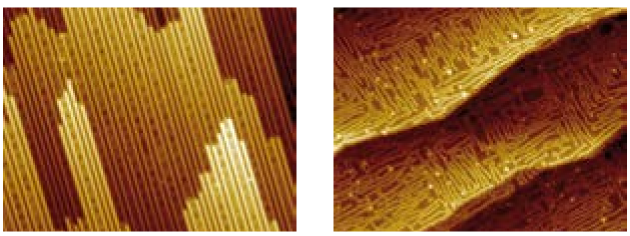
Modern civilization, with its technological achievements in computers, cars, textiles, medicine and pharmacy, owes a large debt to the achievements of chemical synthesis which has, in the course of the centuries, refined the processes for producing inorganic and organic products and pharmaceutical agents.

So far, almost all technical processes in chemistry have been based on a random mixture of molecules, as liquids in test tubes or as gases in reactors – in which, however, any systematic orientation (kinetic control) of the initial molecules has been practically impossible. It would therefore be highly desirable to have a systematic control of molecules, especially of those which do not show the same reactivity in all three directions of a molecular structure. Up to now, the enormous number of molecules in a chemical reaction (typically >1023) has prevented any control over the orientation of individual molecules in which the desired chemical groups of one molecule react with those of another molecule.

Self-organization in large numbers

In the nanosciences, new ways have meanwhile been found to control atoms and molecules on surfaces, molecule by molecule, to carry out chemical reactions on surfaces and evaluate the results using a scanning tunnel microscope or an atomic force microscope with the highest possible – i.e. sub-molecular – resolution. New possibilities have been discovered to systematically arrange the molecules in large numbers on even surfaces, by self-organization, in such a way that they can react with one another in a much more controlled way, due to their arrangement, than is the case in three dimensions. In addition, the dimensionality can be restricted to one, or even zero. Whereas in the first case the systems are reduced to one line, in the second case their degrees of freedom shrink to practically one point.

Such boundary conditions, for example because of atomic series structures, are produced on atomically flat carriers, likewise through self-organization. What is being exploited here is the fact that the surface is a symmetry-breaking element of a crystal and behaves differently, from a thermodynamic point of view, from how its interior does. Heating gives rise to atomic furrows on what were previously atomically flat surfaces, only one atom or just a few atoms wide. Chain-like molecules, for example, can easily fit into these atomically deep furrows and can then only react with one another at both their ends.

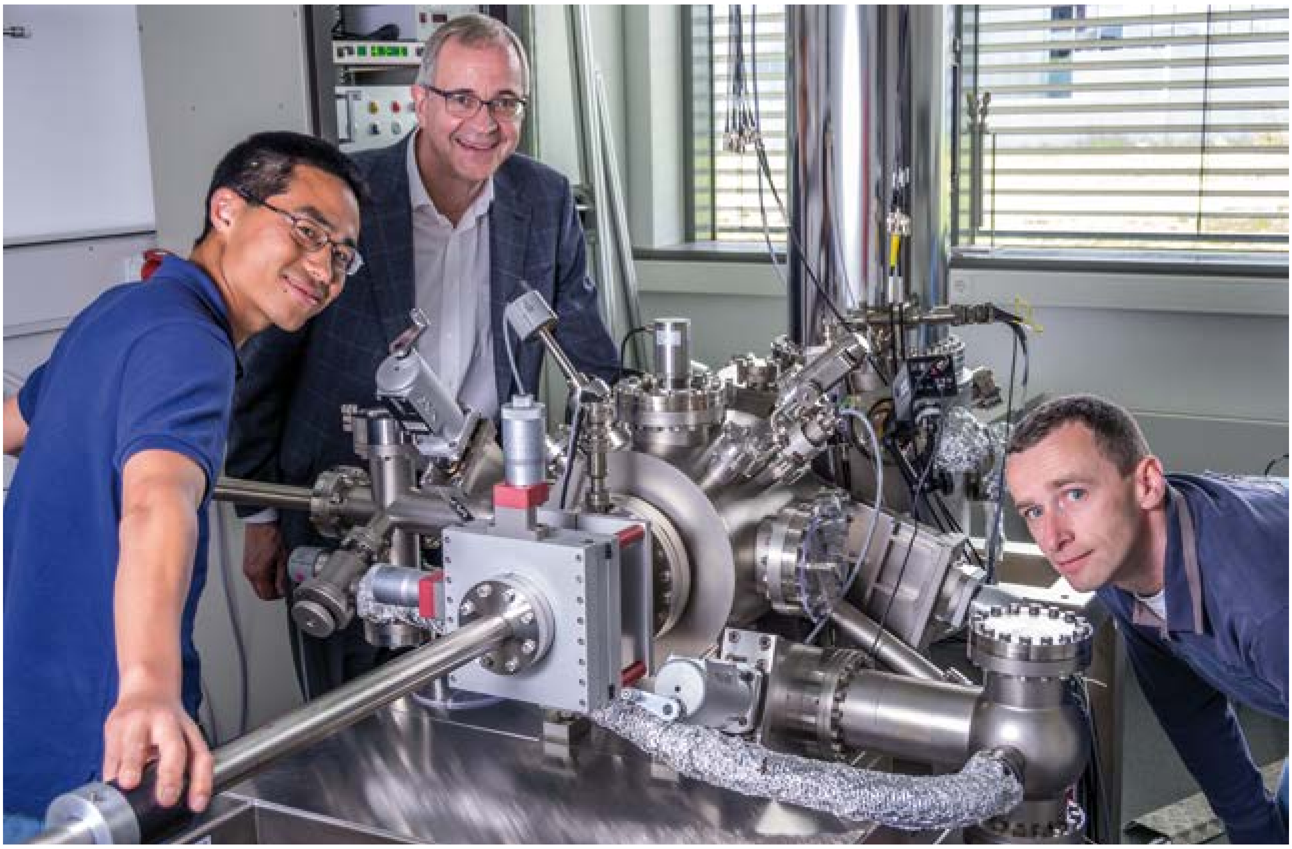


Two examples of nanostructured surfaces

Teams working together

Controlling a structure in this way is not possible using traditional chemical methods. For this reason, teams from the fields of organic chemistry and physics are working together at CeNTech to explore such new synthesis methods. For this purpose, they use complex scanning probe techniques which are operated under ultra-high vacuum and at low temperatures and allow a detailed understanding – under controlled conditions – not only of the interaction of molecular systems but also of their reaction pathways, step by step.

Comprehensive theoretical processes involving computer simulation are used to make quantitative interpretations of observations and predict new variants of the reaction process as an orientation for the experiments. Over the past few years, it has been possible to make decisive progress using this approach. Reaction pathways which had previously been considered impossible could be demonstrated on a variety of examples on surfaces. Among other things, it was possible to carry out chemical reactions under vacuum conditions and at mild temper-



Prof. Dr. Harald Fuchs (centre) with researchers from his team at CeNTech

atures because of the additional catalytic effect of surface atoms – such reactions only functioning under extremely high pressure and with a high-energy input when conventional processes are applied, while still not allowing site-specific reactions

Examples of this are the CH-activation of linear chain molecules, Glaser coupling, and types of reaction which systematically synthesize the carbon nanoribbons on surfaces. These reactions are highly interesting for industry and molecular electronics. By selecting suitable surfaces, it was possible to make targeted use of the regioselectivity of starting molecules to achieve a certain form of a product – which is not possible using conventional methods. Finally, chemical products were demonstrated which were considered to be unstable in conventional chemistry. This leads to new functional systems and exciting new technologically attractive processes of chemical synthesis. With high-resolution force microscopy, it is now possible to make even individual bonds between the atoms of a molecule visible.

Such projects, in which nanophysical methods, chemical know-how and the opportunities provided by theoretical calculations all work together, are ideal examples of successful interdisciplinary work that has resulted in new transdisciplinary approaches for the future which cut across departmental boundaries and in which Münster has taken a leading role on the international stage.

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Polymer brushes on glass or wafers

The team headed by Armido Studer is working on innovative hybrid materials and their hitherto unknown properties

One of nanotechnology's major fields of research is that of organizing atoms and molecules in a detailed way on functional surfaces. New types of material can be produced whose properties can be systematically controlled. Prof. Dr. Armido Studer and his team of researchers have been working on smart materials for several years now. They also collaborate closely with other teams, for example that headed by Prof. Dr. Harald Fuchs, which is working in the area of surface physics.

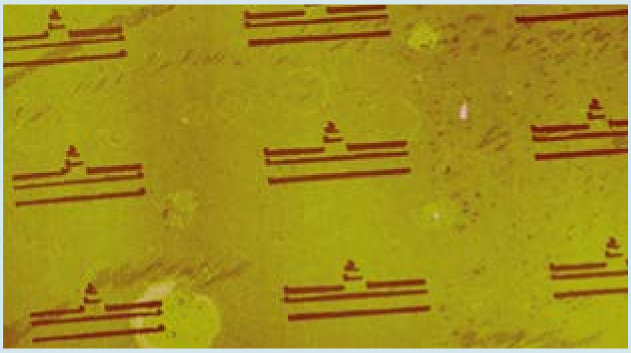
They have already succeeded, for example, in evaporating small molecules on metallic surfaces by means of organic molecular beam epitaxy and then transforming them into oligomers and polymers with defined architecture. The choice of metallic surface here plays anything but a subordinate role, as it not only has a formative function but is also directly involved in the reaction mechanism. Such reactivities are a very important step towards two-dimensional polymer networks which were not previously accessible by means of traditional strategies in solution, but which have the potential to revolutionize molecular electronics.

Architects of varied systems

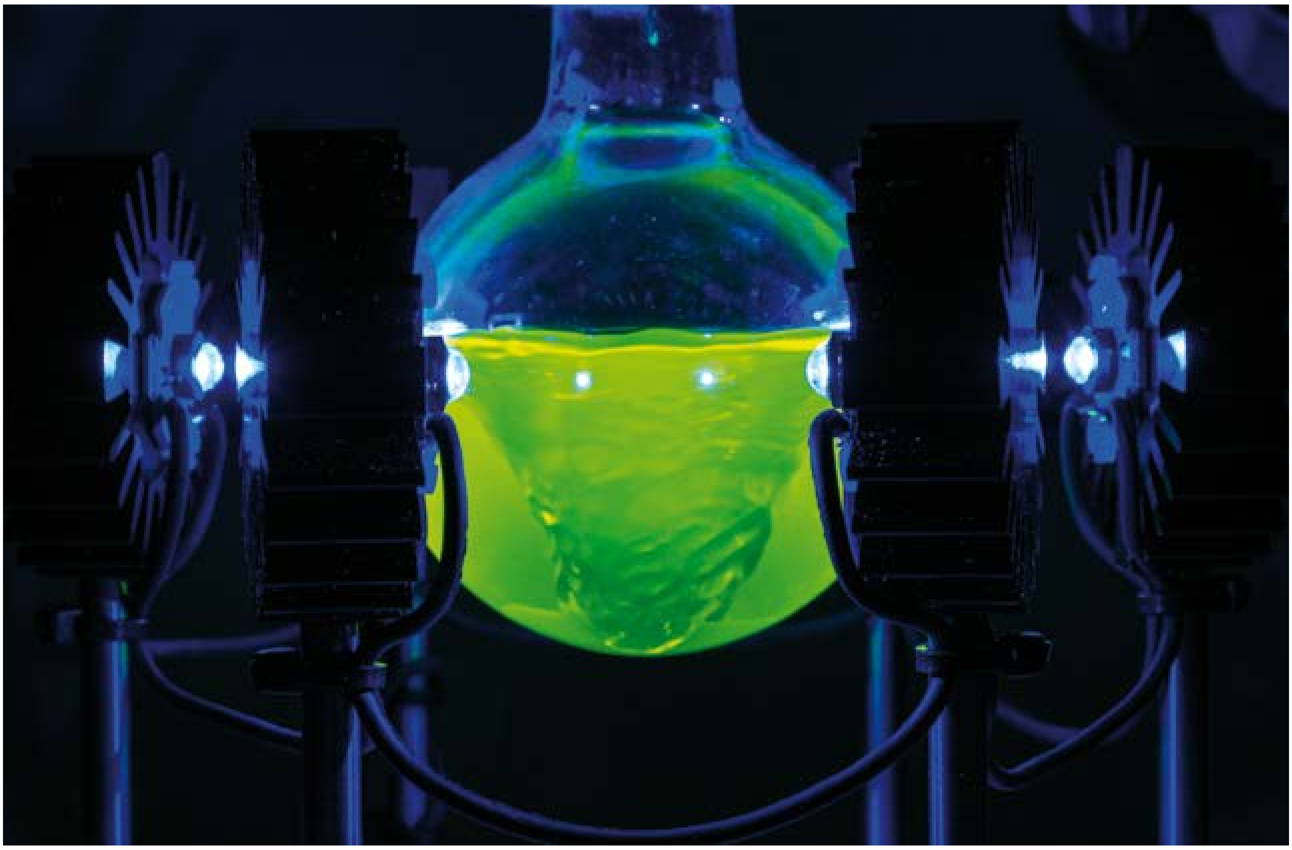
Further examples of organic/inorganic hybrid materials are so-called polymer brushes. Here, different techniques are used to anchor polymers on an inorganic carrier material. Prof. Dr. Studer's team uses primarily nitroxide-mediated polymerization (NMP) to carry out controlled synthesis of various polymer structures on surfaces such as glass, silicon wafers or nanoparticles. Polymer brushes have such a high density that the individual polymer strands are stretched and result in new macroscopic properties

Collaborative Research Centre receives 17 million euros

Prof. Dr. Armido Studer is also the spokesperson for the Collaborative Research Centre "Synergistic Effects in Chemistry" at the University of Münster set up by the German Research Foundation (DFG) in 2010, initially until 2017. Over seven years, the DFG provided funding of around 17 million euros for the project. A number of acknowledged experts from the fields of chemistry, physics and medicine are involved in the Collaborative Research Centre, including some promising junior researchers. The researchers' aim is to analyse to what extent the spatial and temporal interplay between several chemical components has an influence on the result of chemical reactions, compared with a stepwise reaction. In many cases, opportunities for controlling the production of materials, with several factors having an influence simultaneously, are not exploited. Today, however, we are able to develop completely new chemical reactions – using chemical components that act together – and create new products or phenomena such as conductivity, molecular recognition or magnetism. In the Collaborative Research Centre such effects are being studied for the first time on an interdisciplinary basis. The University of Münster provides an ideal environment for this, with 19 teams of researchers from four Institutes of Chemistry and one Institute each from the departments of Physics and Medicine.



Structured polymer brushes (collaboration between Prof. Dr. Studer and Prof. Dr. Chi). The dark lines have a density of 200 nanometres.



of the surface. Moreover, the use of reactive monomers provides simple, modular and efficient access to functional polymers – in solution, as well as surface-bound. Among other things, Armido Studer's team of researchers have established acyloin functionalities in photoactive systems from polymers or polymer brushes. These can be further derivatized after polymerization.

Combination with microstructures

For this, the substrate only needs to be radiated with ultraviolet light (wavelength: 365 nanometres) in the presence of a nitroxide with the desired functional group. Any optimization of the polymerization no longer applies and hitherto inaccessible polymers become accessible. In addition, structured exposure and therefore modification are possible. At the same time, the researchers also provide a use for such structures: the aim is that the functionalization of nanoparticles such as zeolite L crystals should lead to complementary zeolite polymer conjugates, which can then be used as reactive building blocks. Controlled through manual combination via optical tweezers (collaboration with Prof. Dr. Cornelia Denz) or self-assembly, complex microscopic structures can be created and chemically fixed. Ultimately, structures of this kind are to be used in photonics and diagnostics, making a decisive contribution to new components.

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Intelligent label measures best-before date

PolyTaksys can make intelligent labels for food, using very fine nanotubes

Nanotechnology is opening the door to completely new ideas and products. Using extremely small, self-organizing nanochannels produces extremely fine tubes. The distances between the channels, their diameter and the angles to one another can be set precisely. Channel ramifications or ends are also possible. In this way, new kinds of electronic functional elements arise which are known as "smart labels". Researchers in Prof. Dr. Meinhard Knoll's team are developing a new class of such intelligent labels for goods and products.

Based on organic electronic materials, Meinhard Knoll found the effect of so-called doping front migration, in which a front moving just a few nanometres per second changes the electrical and optical properties of thin layers. The new PolyTaksys technology uses this effect to provide unique properties. The nanoelements do not need any battery, and they enable a clock and an analogue or digital display to be integrated, allow electrical switching effects and can be read electromagnetically by modifying a traditional RFID transponder.

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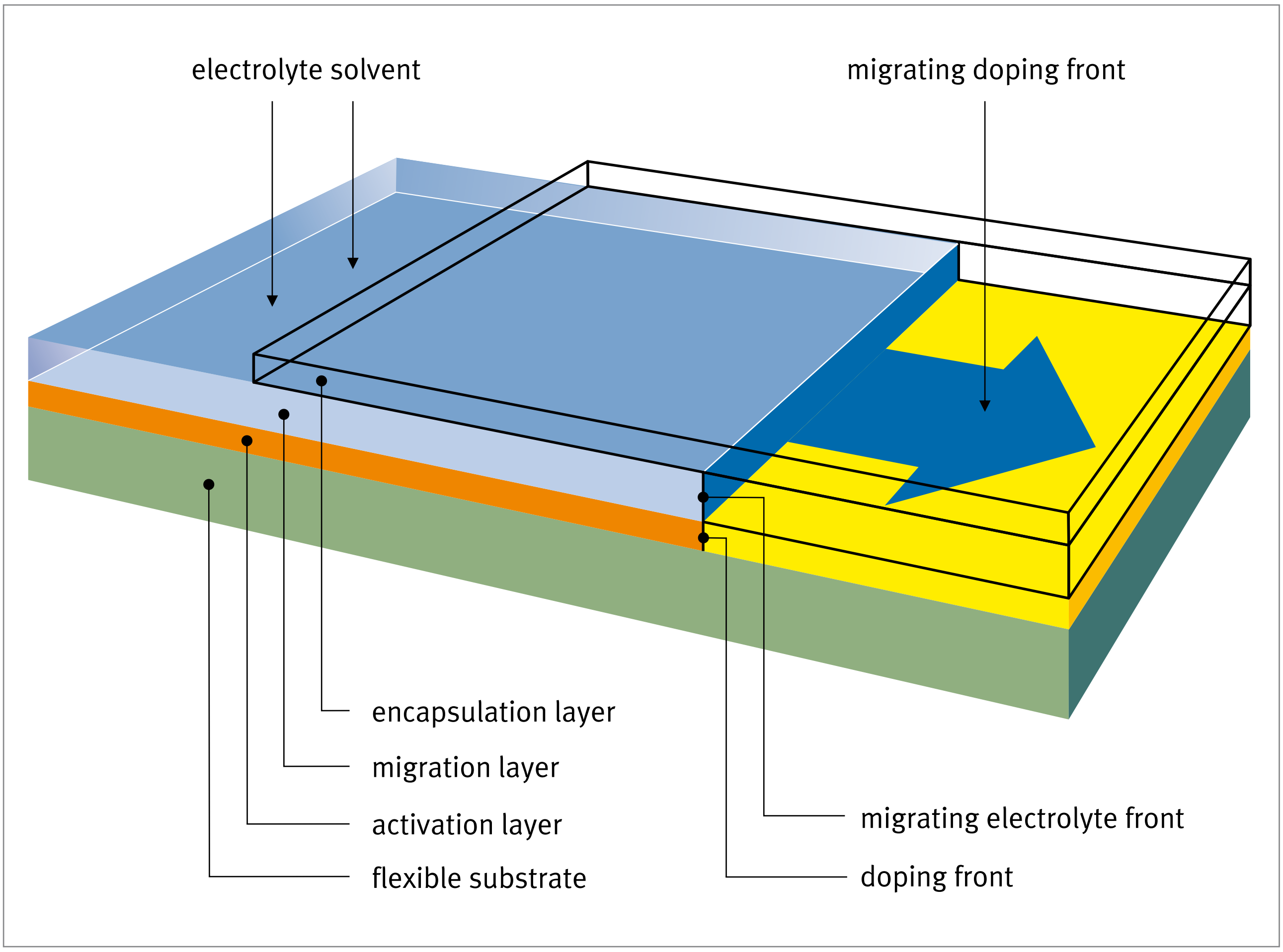
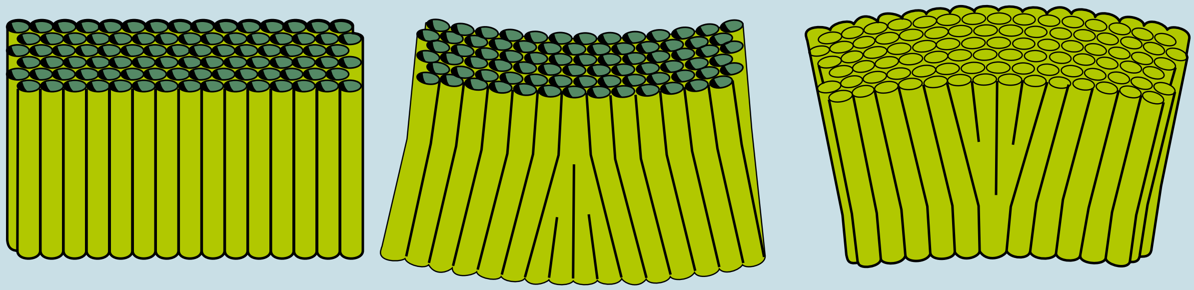
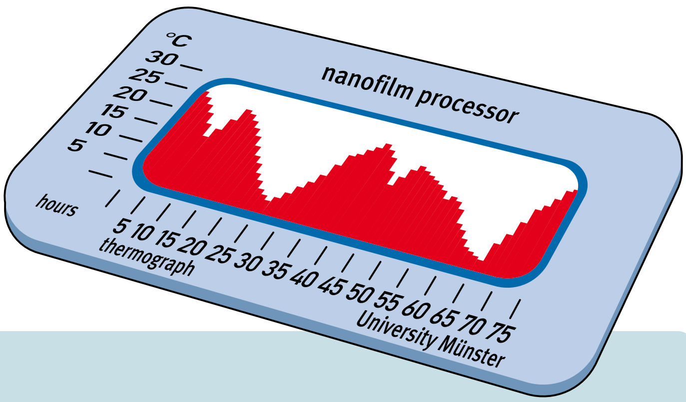




Parallel, diverging and converging nanochannels with ramifications and ends

A new generation of smart labels

These are ideal conditions for creating a new generation of smart labels. The first application for PolyTaksys is in the form of an electronic best-before date that can be integrated into food packaging. It measures the time that has passed after activation of the label and takes account of the temperature – which is often decisive for shelf life. PolyTaksys looks like a thin label made of plastic foil, which records the measurement parameters and makes them visible to the human eye. It can also make electromagnetic readings.



Thermograph nanofilm processor

A temperature curve automatically writes itself on a small piece of plastic foil

Nanofilm processors embody a new form of electronics, working without a battery. Invented by Prof. Dr. Meinhard Knoll from the Institute of Physical Chemistry and the Center for Nanotechnology at the University of Münster, they are secured internationally by patent applications.

One example of their use is the thermograph nanofilm processor. It has the form of a foil label, and temperature curves write themselves automatically on it. Its properties are unique: a continuous measurement of temperature as a function of time, a continuously progressing display of a temperature curve as a function of time, and continuous functioning without any battery. The principle on which it functions is based on the lateral autoxidation of nanoscale layers with a temperature-dependent modulation of the oxidation speed.

The structure of the foil label is a system of multiple layers. If the item is mass-produced, unit costs are forecast to be between ten cents and one euro, depending on the number of pieces produced. This means they can replace temperature loggers with a display, which are based on conventional electronics and cost around 200 euros.

Typical applications for the thermograph nanofilm processor are general uses in monitoring temperatures in pharmacy and medicine or in checking food. Prof. Dr. Meinhard Knoll's team of researchers has received 740,000 euros in funding for this project from the German Ministry of Education and Research.

Of quantum dots and nanowires

Material physicists from Münster are working on a new class of functional materials

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Most of the metals and ceramics which are used for technical purposes consist of tiny crystallites, between a few micrometres and a few millimetres in size. If their size is reduced to some nanometres – i.e. one thousandth of a micrometre – this gives rise to a new class of materials, characterized by the fact that the quantity of atoms at the interfaces is comparable to that inside the crystallites. Because of this high interface proportion, nanocrystalline materials have special properties such as do not occur in any materials existing so far. The properties of nanocrystalline materials depend on the size, dimensionality, chemical composition and atomic structure of the crystallites. Further factors are the chemical and atomic structure of their interfaces, which exist in large numbers between the crystallites. It is precisely the variations in these parameters which lead to big changes, for example, in magnetic, optical, electrical, mechanical and catalytic behaviour. Relatively little is understood about the precise physical causes of these changes in the properties.

If nanocrystalline materials are to be used for technical applications, then such an understanding

Concentration while preparing experiments is one secret of scientific success.

is vital. In addition, nanostructured materials are already very important today, for example as organic LEDs or as catalysts. Researchers in the team headed by Prof. Dr.-Ing. Gerhard Wilde are looking at a whole series of fundamental questions, answers to which are important for a variety of applications.

Developing new methods

These include sensor technology for gases or fine dusts, optically functionalized surfaces, high-strength materials that are also tough (ductile) for implants or as storage for data and energy. The nanocrystalline and nanostructured materials are synthesized using methods, some of which the researchers are yet to develop. In addition, the structure and selected properties of the new materials will need to be analysed. For this, very high-resolution electron microscopy plays a particularly important role.

One focus is on the nanostructured surfaces. A new method offers better opportunities for the controlled and inexpensive production of nanostructures on almost any kind of surface. The spectrum ranges from semiconducting quantum dots, metallic nanowires and oxydic or metallic core-shell particles to nanoporous multilayer systems with extremely high specific surfaces.

Nanocrystalline materials

Research being undertaken on nanocrystalline materials is a second focus of the work being done, with particular attention being given to the mechanical properties of massive nanocrystalline materials. Nanocrystalline titanium, for example, is especially attractive for medical implants because it has greater strength and toughness. This combination is ideal for implants and cannot be achieved with traditional materials. Transferring this favourable combination to other materials requires an atomistic understanding of the structure and transport processes along internal interfaces. In their work, researchers at the Chair of Material Physics at the University of Münster can draw on analytical technology and competence that is unique worldwide. They can synthesize the materials, analyse the microstructures, characterize the properties of the material and measure the transport processes within it, in particular along the internal interfaces. This is very important when trying to understand the underlying processes and mechanisms and use them for new functional materials.

Better gas sensors thanks to nanostructures

It has long been known that air pollutants are a danger to both health and the environment. Nitrogen dioxide and carbon monoxide are especially hazardous. The concentration of these gases in the environment correlates closely with the concentration of fine dust, which is partly man-made and can cause diseases of the respiratory system. Motor traffic is the largest cause of nitrogen dioxide and carbon monoxide, which is why gas sensors are so important for detecting pollution. The technology has not yet been perfected, however. For example, the minimal harmful concentration of nitrogen dioxide in the air for the human body is around 50 ppb (parts per billion), which is 50 out of one billion particles. The detection limit which a commercial gas sensor has is reached with 500 ppb. In order to refine the detection limit, 3D surface nanostructuring technology has been developed. The gas sensors on the nanostructured surface are capable of measuring minimal concentrations of harmful gases in the air. For this purpose, the researchers use freestanding nanowires and nanotubes on a silicon substrate, for example. Such structures are also analysed for applications in magnetic field sensors and in thermoelectric and photovoltaic energy generation.

Atoms and molecules as building material for medicine boxes

Multiple layers and nanocontainers made of charged polymers prove to be stable and have many uses

Nanotechnology makes it possible: even individual atoms and molecules can be used as building materials. The group of researchers headed by Prof. Dr. Monika Schönhoff uses molecular chains to construct ultra-thin layers or nanocontainers. Specifically, electrically charged molecules are used – so-called polyelectrolytes. They allow very stable multiple layers to be made which are only millionths of a millimetre thick. The individual layers are alternately positively and negatively charged, which is why they attract one another. This gives rise to new kinds of materials, which are soft, but stable. Moreover, they can absorb water or smaller molecules. They can thus be made to swell up or house certain guest molecules. Working together with researchers from Tsinghua University in Beijing (TRR 61), the group analyses how binding sites for guest molecules become implanted in such layers. As a result, for example multilayers could be developed as selective filters for certain molecules. For this, the properties of nanolayers are analysed using special methods such as ellipsometry, quartz crystal microbalance (QCM-D), impedance spectroscopy or ATR-IR.

Nanocontainers for active molecules

Very small particles with a size of around one hundred nanometres are capable of penetrating into cells and transporting medical substances. Small active molecules can be integrated into very many different types of nanoparticles, as in a container – for example, into polymeric hollow capsules made of polyions. First, the researchers look at some fundamental questions on the integration, dynamics and transportation of such guest molecules. Using a special method which Prof. Dr. Schönhoff's team have pushed ahead with – based on measuring molecular diffusion by means of nuclear magnetic resonance – it is determined how the substances diffuse through the walls of the nanocontainer, and where they are in the particle. In doing so, it is possible to study not only molecular agents but also suitable model substances for a wide range of applications.

Ultra-thin ion-conducting polymer layers

For new types of battery, very thin membranes are needed which can conduct small ions, for example electrically charged lithium. The researchers are looking for answers to important questions: How fast

The team of researchers of Prof. Dr. Monika Schönhoff do the ions move in polymeric material? Does transportation occur in the form of individual ions or as an uncharged pair? These questions are clarified by comparing diffusion and conductivity. Understanding how the negatively and positively charged ions move helps to optimize the polymers in the membrane. Both salt-in-polymer electrolytes and polyelectrolyte multilayers into which ions are introduced in the form of salts are examined. As these membranes are particularly thin, the charging time for a battery could, for example, be accelerated as a result.

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A model system for mini-proteins

Nature shows the way: the self-organization of innumerable molecular components gives rise to the functional and dynamic structures which make life at all possible. The aim of the research being carried out by the team headed by Prof. Dr. Bart Jan Ravoo is to use self-organizing molecules as the smallest possible components for nanoscale structures. The structure of complex, dynamic molecular systems leads to materials with new properties. The team is doing research in the field of supramolecular chemistry and is modifying surfaces by means of molecular self-organization. As the researchers are working on natural principles and processes, in order to make them usable for technical innovations, this approach is called biomimetics.

In supramolecular chemistry, the team is looking primarily at the recognition and self-organization of molecules, nanoparticles and colloids in a watery solution. For this purpose, they use non-covalent interactions between the molecules to create bigger structures. Several weak interactions lead to strong and selective multivalent interactions. One topic of research concerns vesicles (small bubbles) with integrated receptor molecules – so-called host molecules such as cyclodextrins. The recognition of guest molecules on the surface of the vesicles and the interaction between the vesicles are a fascinating model system for biological cell-cell recognition. In addition, the researchers are delving into the potential of these vesicles for targeted pharmacotherapy. A new topic is the synthesis of carbohydrate receptors. These artificial mini-proteins effectively bond with selected carbohydrates both in water and on membrane surfaces. This means they are of great interest for biomedical purposes. At the centre of the modification of molecular and self-organizing surfaces are the production and the properties of molecular monolayers on nanoparticles and solid substrates. The natural processes of self-organization are combined with lithographic processes such as microcontact printing. In doing so, reactive molecular inks are used which are stamped onto a surface in a pattern. The stamping also initiates a chemical reaction of the molecules on the surface. In this way, chemical and biological templates such as biochips with proteins, nucleotides or carbohydrates are made. The electrical properties of molecular monolayers are also examined.

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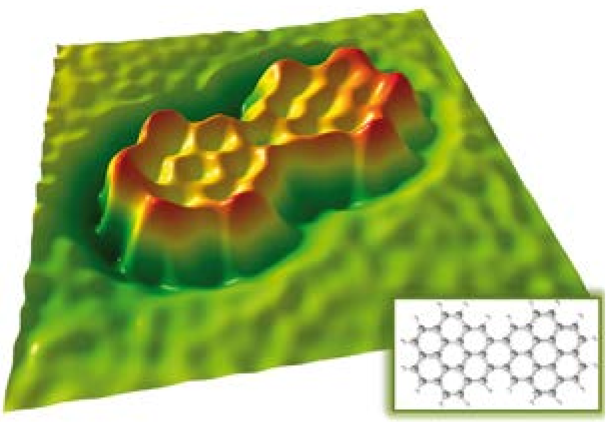
Interface analytics for new materials

High-resolution scanning probe microscopy allows not only to resolve nanoscale structures, but also to measure forces and conductivities with highest precision

Because of the increasing miniaturization of electronic circuits, their properties are increasingly determined by nanoscale interface effects. A fundamental understanding of these effects allows developing materials with tailored functional properties. A fundamental understanding of these effects allows the development of materials with tailored functional properties. At the Center for Nanotechnology (CeNTech), the "Nanoscale Interface Analytics" team headed by Dr. Harry Mönig is carrying out research using state-of-the-art atomic force and scanning tunneling microscopy. The experiments enable the visualization of (sub-)molecular and atomic structures as well as extremely precise force and conductivity measurements. These microscopic analyses are combined with experiments using photoelectron spectroscopy to gain additional information on chemical and electronic properties of the interfaces on a global scale. In order to ensure extremely clean and highly defined experimental conditions, all experiments are performed under ultrahigh vacuum conditions and partly at temperatures close to absolute zero.



Atomic force microscopy image showing the internal structure of a single dicoronylene molecule. To produce such high-resolution images, the probe tip has to be passivated with a single, covalently bonded oxygen atom.

To achieve highly defined experimental conditions, the experiments are carried out under ultrahigh vacuum conditions and at temperatures close to absolute zero.

Which forces organize molecules?

Processes which cause atoms or molecules to arrange spontaneously in well-ordered patterns are termed 'self-organization'. Such self-organized structures are the basis for the development of new nanostructured materials with certain optoelectronic properties. Here, close collaboration with scientists working in the field of organic chemistry allows varying the properties of the molecules in a very broad range, providing a high degree of control.

One of the major goals is to exploit the broad spectrum of functional molecules to develop tailored materials for applications in electronic components such as LEDs or organic solar cells. High-resolution microscopy experiments are the key to understand and systematically control the mechanisms of self-organization on a fundamental level.

Analytics for thin-film solar cells

Thin-film solar cells based on chalcopyrite materials hold promise for further reduction in costs for energy production through photovoltaics. Although the high solar cell efficiency of this technology has already led to mass production, many effects are by far not sufficiently understood. The major challenge here is to understand the complex defect physics of the involved chalcopyrite materials. On the one hand, certain defects in this material determine its doping concentration and are therefore important for the operation of these solar cells. On the other hand, defects at the interfaces of such a device lead to recombination losses and therefore deteriorate the solar cell efficiency. In order to further optimize the efficiency, a better understanding of this class of materials and the effects at relevant interfaces is crucial. The experiments in the laboratories at CeN-Tech are carried out in collaboration with the Helmholtz Centre for Materials and Energy in Berlin.

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A loom for tiny patterns

The properties of individual atoms, molecules and materials give rise to patterns which can organize themselves and merge

The team of researchers headed by Prof. Dr. Lifeng Chi exploits this self-organizing ability to produce nanostructured surfaces which, when enlarged, often look like woven textiles. They are tailor-made, so to speak. The mesh size is very small, however – between just a few millionths and a few thousandths of a millimetre.

On the one hand, the researchers construct tiny molecular morphologies by systematically exploiting certain properties of organic material. On the other hand, their aim is to influence the alignment of the molecules. This is why experienced chemists from Prof. Dr. Gerhard Erker's team are also engaged in this work. The aim is to create new methods of organizing and structuring the molecules in such a way that they display new electrical and optical properties. In order to have a better understanding of the formation of patterns, there are close links to the theoretical teams led by Prof. Dr. Uwe Thiele and Prof. Dr. Andreas Heuer.

Inspired by nature

In their research into new materials for medicine, researchers take their example from nature. After all, natural biological systems have developed over millions of years, undergoing a strict process of selection in their evolution and being constantly and repeatedly scrutinized and adapted. Learning from these processes can inspire and advance the development of new materials. One important point is research into effects, which occur at the atomic level between various biomaterials. In nature, the fine structuring of surfaces, the colonization with cells or biochemical molecules, often plays a greater role than the properties of the cells and tissue per se.

The effect can also be used to reduce immunological and other rejection reactions in living tissue. This is important for new applications in biomedicine. One focus is the preferred alignment of chiral molecules, of which two variants always occur, just like two hands: right and left. In nature, there are two arrangements of chiral molecules, which are chemically similar but arranged as mirror images of each other. The so-called chirality of biomolecules is quite often important to achieve a desired effect. Both molecules can cause entirely different effects, in medicine for example.

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Light steers light – optics at the nanoscale

Interplay with nanostructures fosters new avenues for information processing

Light possesses a range of unique properties unlike any other energy source. It can be concentrated down to one millionth of a millimetre, and it can be used to write words on a human hair with the help of lasers.

Laser light can be used for nanoscale structuring. Light packages can be generated in very short pulses of one quadrillionth of a second – a femtosecond – enabling the transfer of up to one million data in just one second. Light is much faster than electronics – not only in data transfer, but also in data processing – as it can carry out operations parallel to one another. This is the aim for optical information processing: optical computers in which light is controlled by light.

Photonic nanoscale computers

Aiming at computing with light particles (photons) requires methods of optical storage and the development of optical processors. Optical data storage can be undertaken quite impressively with volume holography, which enables extremely high data storage on very little space. For an optical microprocessor, material has to be finely structured to allow the travelling of light of a certain wavelength.

In this way, photonic crystals are realized – artificial periodic materials which interact with photons analogously, as semiconductors do with electrons. Photonic crystals can guide and conduct the light at will. Then, by integrating on a chip light guiding with other optical elements optical chips can be accomplished.

Producing photonic crystals represents a huge challenge. Prof. Dr. Denz's team works with femtosecond laser lithography to write photonic structures in glass and crystals. By using this technique, arbitrary three-dimensional structures made of polymers can be also produced.

Further possibilities for the realization of photonic crystals are found in nature, whose fundamental design principle is based on self-organization. Opals – shimmering crystals with an impressive variety of colours –produce suitable photonic structures when they are growing. The same process of self-organization can be used to produce synthetic photonic crystals from polymers. Due to their often complex structures, they are suitable for optical chips.

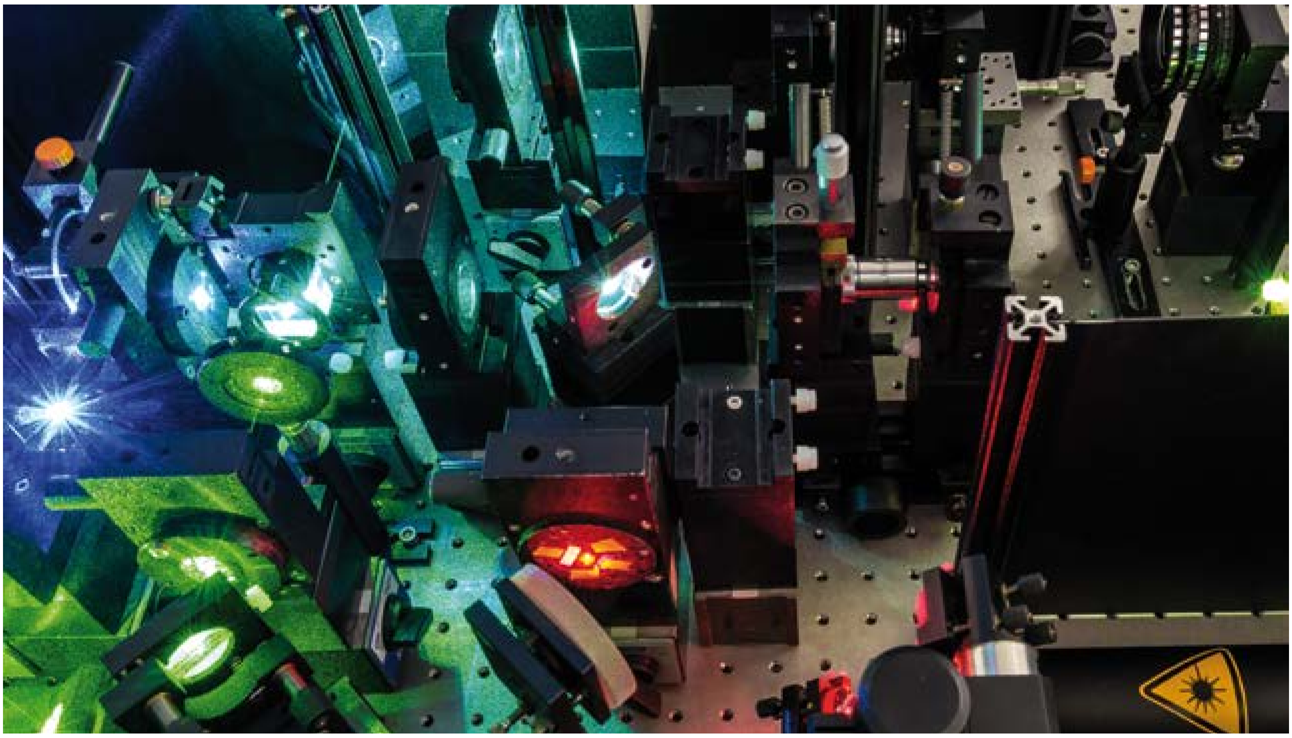
Yet another possibility for photonical crystal generation consists in the induction of changes into the optical properties of the material with light, such as those generated through non-linear optics. This method enables to write periodic structures directly in the material using laser beams. Prof. Dr. Denz's team is also using this technology to slow down light considerably and to regulate its frequency in such a way that optical computing operations can be carried out.

Currently, the most elegant method of nanostructuring takes place in so-called photorefractive crystals with low light intensities. In this case, it is possible to use projection methods based on liquid crystal displays to write highly complex, multidimensional photonic structures. They cannot only guide light but also provide the non-linear optical effects needed for data processing – an essential requirement for the photonic chip.

Light-catching structures

With the constantly increasing energy consumption, the demand for more efficient energy sources – preferably renewable ones – is also increasing. The direct conversion of sunlight using the photoelectric effect represents one of the simplest and most inexpensive options for energy production. These make the photoelectric effect a main pillar for future energy supply.

For this reason, research on new, efficient organic solar cells is particularly important. Organic solar cells can be produced in a more simply and cheaply manner. They also offer further benefits such as their versatility to a particular application. To improve organic solar cells, Prof. Dr. Denz' team investigates novel materials which feature not only high absorption but also high conductivity. In addition, they are pursuing design strategies, which prospect increased efficiency. There are several options for achieving this goal. On the one hand, coupling light into the solar cell is improved by means of appropri-



Experimental set-up to produce light-trapping structures for applications in organic solar cells.

ate anti-reflective layers. A second point concerns the propagation of light within the cell. In this case, so-called light-trapping structures are inserted into the photovoltaic cells, which modify the optical path in such a way that increased efficiency becomes possible.

Optical tweezers

Since Arthur Ashkin's discovered that the radiation pressure of light in a tightly focused laser beam is able to hold, move and rotate microscopic objects three-dimensionally, a very broad range of applications have been developed for optical tweezers. The most important applications of optical tweezers are currently in the fields of biophotonics and cell biology, where organelles and compartments in cells are manipulated and controlled.

By using optical tweezers, contact-free – and thus sterile – manipulation of very tiny objects can be carried out with the greatest precision within the nanometre range. For quantitative studies, it is of inestimable value that extremely small forces in the nano and piconewton range can be systematically exerted and measured.

In addition to the measurement of the locomotive forces and rotational properties of bacterial molecular nanomotors, a current research focus is the investigation of the viscoelasticity of living cells. We also use holographic methods to elegantly extend the basic principle of optical tweezers to the optical control of many particles. To this end, we modulate the phase front of a laser by means of computer-calculated holograms. This gives rise to a huge number of individual optical tweezers in the sample, which can be individually controlled and organized in a variety of forms, enabling us to structure them.

Such simultaneous control of the position and orientation of many particles allows to arrange and structure special nanocontainers. These nanocontainers may contain a variety of different chemical charges. Recently, we have managed to arrange these nanocontainers only by using light. This gives rise to a system which is hierarchically ordered – from individual molecules to the micrometre range –, thus providing new exciting properties to the entire system.

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Tailor-made materials for microelectronics

Materials researchers are investigating atomic defects, interfaces and nanocrystals to push new technologies

Modern technology would be unthinkable without tailor-made materials. It is in the chip industry in particular that specially modified semiconductors play an essential role. Their properties are largely determined by foreign atoms, which are specifically introduced into the atomic lattice structure in order to create defects. In this way, for example, the electrical resistance can be varied. The interfaces between various materials also play a major role. In so-called MOS transistors, they determine the electrical properties. The MOS components combine silicon and silicon dioxide, for example. They are absolutely indispensable in modern microelectronics.

The effects which atomic defects, interfaces and microstructures have need to be known and understood for materials systems in solar power technology, as well as for thermoelectric applications, fuel cells or special ion batteries made of solid materials. Prof. Dr. Hartmut Bracht and his team of researchers are studying the interplay between atomic, microscopic and macroscopic properties with the specific aim of developing new functional materials or optimizing materials already known.

One example is the idea of using germanium instead of silicon as a semiconductor for electronic components. What the researchers are hoping for is a further increase in the performance of microprocessors. However, before germanium can be systematically doped with foreign atoms, the underlying mechanisms of the atomic mobility of defects and dopants in this material have to be explained exactly. For this purpose, the researchers are experimenting with special structures, which consist of semiconductor layers with a thickness of just a few nanometres and are enriched with isotopes. A nanometre is the millionth part of one millimetre. Based on these test structures, the researchers analyse what influence the foreign atoms have on the mobility of the germanium atoms. To this end, they use special time-of-flight mass spectrometers for element analysis in the structures. Such experiments are not only of fundamental importance for new processes for doping semiconductors. They also supply information on the thermodynamic properties of the atomic defects. This is important for comparing the results with theoretical predictions. The work is carried out in collaboration with universities and companies both at home and abroad, including Denmark, the USA and Japan. Funding is provided from the research programmes of the European Union and the German Research Foundation.

Nanocrystals store data

For materials scientists, one central topic for the future is the storage of electrical energy and electronic data with as little loss as possible. The team of researchers led by Hartmut Bracht developed an inexpensive wet-chemical method of synthesizing dielectric layers with special nanoparticles. The process has already been accepted for patenting. The characteristics of the nanoparticles can be controlled using the parameters of the wet-chemical process. Studies carried out by the researchers prove that electrical charges can be stored in and at the interfaces of nanocrystals.

As part of the German Research Foundation's Priority Programme 1386, the team of researchers led by Hartmut Bracht are investigating new concepts for increasing the efficiency of thermoelectric components, i.e. for a more efficient direct conversion of heat into electricity.

A young team of researchers of the next generation. In the middle: Prof. Dr. Hartmut Bracht.

Silicon: a good conductor of heat

The challenge consists in developing semiconducting materials, which have low heat conductivity but good electrical conductivity. Unfortunately, the semiconductor silicon, the starting material for many electronic components and available in abundance on the Earth, is too good a heat conductor for thermoelectric applications.

In order to use silicon nonetheless, the influence of isotope-modulated silicon layers on heat conductivity is being investigated. Natural silicon consists of three stable isotopes with varying masses. This enables nanostructures of isotope-enriched silicon to be produced using suitable layer deposition processes. Studies relating to heat conductivity in mass-modulated silicon layers demonstrate reduced heat conductivity compared with natural silicon.

Comprehensive experimental and theoretical studies are now to be carried out to clarify in detail the influence of isotope distribution on heat conductivity in silicon and to help evaluate the benefit of isotope-modulated semiconductors for thermoelectric applications.

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Light forces and optics with single photons

LEDs and lasers are widely used as energy-efficient light sources and are indispensable today in our society as optical information carriers. For artificial lighting and data transmission, usually high light intensities are used.

If the intensity of the radiation is reduced to very low values, the complex quantum properties of individual light particles (photons) appear. These can be used not only for new types of quantum computers with enormous processing capacity. In their interaction with nanostructured material, photons make it possible to exploit a property of light which is often overlooked: momentum transfer via radiation.

Light can build up pressure – so-called radiation pressure, which Johannes Kepler already noticed in the 17th century while observing comet tails. This form of radiation pressure not only makes it possible to make material oscillate without contact.

The radiation pressure can also be used to create flexible photonic circuits. Normally we do not notice the radiation pressure because its effect is very low in sunlight.

However, if nanoscale components are used, even the smallest forces have large impacts. Such optical forces are investigated using photonic circuits and are used for precision measurement.

Optical circuits

Photonic circuits are the optical counterpart to electrical circuits such as are found in every computer and household appliance. Instead of electrical wires, optical waveguides are used to interconnect components. These are much smaller than electrical connections – often just a fraction of the width of the optical wavelength.

With the aid of such optical cables, photons can be routed almost at will across nanostructured surfaces. In order to be able to exploit the radiation pressure in waveguides, these waveguides have to be converted into mechanically mobile components.

This is achieved using modern nanotechnology processes in which the waveguide is detached from its substrate. Such self-supporting waveguides can oscillate freely, like the strings of an instrument, but with a much higher frequency, which the human ear cannot hear. As waveguides represent nanoscale elements, very small forces are sufficient to stimulate them mechanically, as the radiation pressure provides, for example.

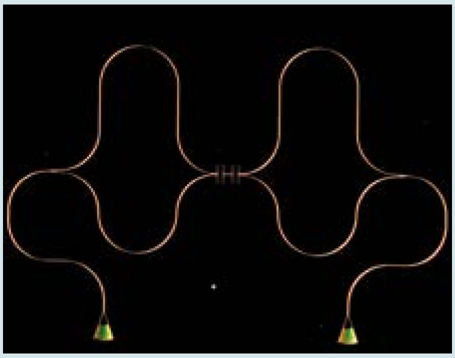
In their interaction with optical circuits, such forces can be used to produce highly sensitive sensors and new types of optical components for optical data processing. One interesting application is mechanical date storage, which operates optically. Such structures can hold data for very long times. They are not subject to the limitations imposed by electronic storage media.

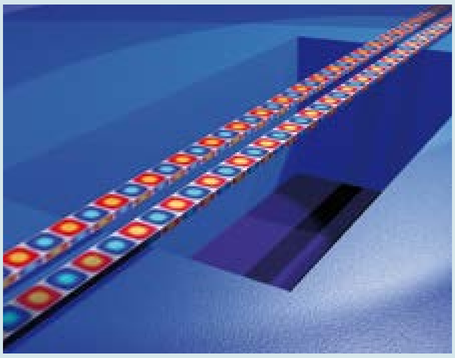
Optics with diamond structures

In principle, any material can act as a waveguide as long as it is transparent to light of a desired colour (wavelength, frequency). The team uses unconventional materials which remain stable under extreme conditions, such as diamonds. Diamond offers not only unusual optical properties, but also excellent mechanical ones. It is outstandingly suitable for investigating optical radiation forces. As diamond consists solely of carbon, it can be easily nanostructured, with very small dimensions far below the optical wavelength.

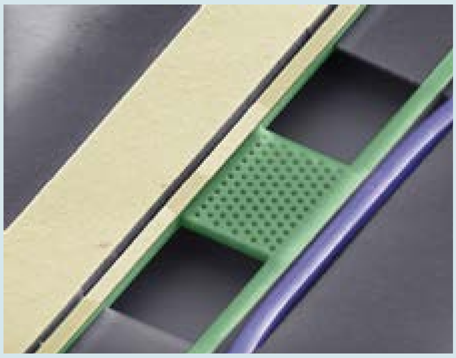
Using nanomechanical diamond components, even very small mechanical motion can be measured, even in aggressive chemical environments, as the material is not attacked by most substances.

The high degree of biocompatibility gives rise to plenty of opportunities in biosensor and medical technology. As diamond is visible not only in the visible wavelength range, but also in the long-wave infrared range, this opens up many perspectives for gas sensor technology and spectroscopy, as well as for detecting individual molecules in the interplay with nanomechanical components. In combination with optical circuits produced entirely from diamond, such integrated optical systems can deliver new applications not only in research but also for everyday life.





Optical circuit with waveguides and photonic elements. On the right can be seen two self-supporting waveguides, which are being stimulated through the radiation pressure.



A freestanding mechanical resonator made of diamond and connected to a waveguide.

Circuits for individual photons

There are many applications for integrated optical circuits in optical data processing, telecommunications and sensor technology. In addition, there is a great potential for more in the transition from traditional optics to quantum optics. In this case, conventional light sources can no longer be used. Instead, light sources are needed which emit just one photon at a time. In order to measure these light quanta, special detectors have to be used which are extremely sensitive and can be easily connected to photonic circuits. This works very well with optical waveguides if additional nanostructures are added – superconducting nanowires, which show no resistance at low temperatures.

Superconductivity is lost through the interaction with one light particle. As a result, the nanowires are suitable for highly sensitive detection methods. The team is developing efficient detectors to be integrated directly in optical circuits. Such structures can form the basic components for future optical quantum computers. They are also suitable for applications in optical fibre technology and sensor technology.

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Light can guide magic bullets

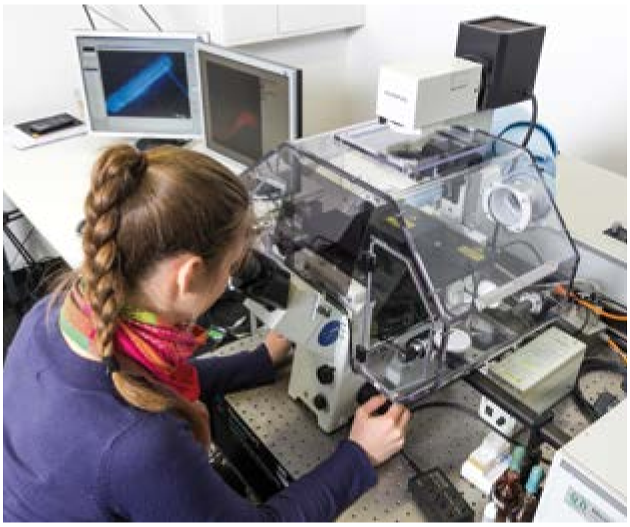
Electroluminescent metal complexes and photoactive nanomaterials give us a glimpse of the future of lighting technology and phototherapy

The team of young researchers led by Dr. Cristian A. Strassert is producing new types of materials and carrying out research into their photophysical properties. Of particular interest are chemical compounds which emit light in the visible range, as well as in combination with inorganic nanostructures.

The researchers' aim is to use such architectures in OLEDs and in biomedicine. The independent team – established in 2011 with the aid of the German Research Foundation (DFG) – today consists of seven young members (two Alexander von Humboldt postdocs, two PhD students, two students working on their master thesis and one on his bachelor degree). Working at the Center for Nanotechnology, they have developed broad interdisciplinary expertise in molecular synthetic chemistry, photophysics and photobiology. The team was set up as part of a total of five DFG-funded projects.

Iridium-free triplet emitters for OLEDs

The Strassert team has wide-ranging experience in the design, visualization and characterization of new types of metal complexes, which emit light when electrically excited. They are incorporated in organic light-emitting diodes (OLEDs), which can potentially convert into light up to 100 percent of the electrical current fed in – and without any heat loss. A fundamental understanding of efficient electroluminescent materials, processable from solution, is at the heart of the researchers' work.



Together with their fundamental knowledge of organometallic chemistry and molecular photophysics, the team is constantly researching and looking for structure-property relationships through modelling, synthesis and characterization at single-molecule level.

Printable diodes

They are the rational basis for the design of sustainable, iridium-free, electrically controllable triplet emitters – for example for inexpensive, energy-efficient, flexible OLEDs. Several fruitful collaborations are being pursued at the University of Münster, which cast new light on material science aspects of the basic research being done, and which are represented in two projects within TRR-SFB 61.

The focus on energy-efficient technologies based on strategies which conserve resources was affirmed through involvement in the establishment and active shaping of the first Rare Earth Elements and Compounds Conference (REEC) and its follow-up. It combines top-level research, innovation, commercial aspects, (urban) mining and recycling. Setting up a dialogue between science and industry, the conferences are especially geared to rare metals of technological importance and their strategic relevance.

Recognizing bacteria and killing them with light

The resistance of bacteria to antibiotics is a great challenge for medical doctors. It is difficult to fight infections which have such pathogens, and in the worst case it is impossible. This is why the search is on for nanostructures that use light and might be applied as light-controlled antibiotics, but also as photosensitizers in aqueous photocatalysis, in photovoltaics and in the treatment of drinking water. Imaging processes in biomedicine can also be supported with the help of these structures. These topics are being looked at as part of a DFG project

being undertaken in collaboration with the Max Planck Institute for Molecular Biomedicine in Dortmund, as well as within two sub-projects in the "Cells in Motion" Cluster of Excellence and in the SFB 656 MoBil Collaborative Research Centre. International collaboration is also being undertaken in this field with universities in São Paulo, Buenos Aires, Barcelona and San Diego.

The researchers have developed nanomaterials which target and kill resistant bacteria. The effectiveness of the nanoparticles is based on the method of photodynamic therapy. Under visible light irradiation, a reaction is triggered, as a result of which the bacteria cells die off. The basis is hybrid organic or inorganic photosensitizers, which are activated by red light and produce highly reactive and aggressive oxygen molecules. These molecules, known as singlet oxygen, start a series of lethal reaction chains. Such results open up fascinating possibilities for treating infectious diseases and show the development of a new generation of phototherapeutic agents in a completely new light.

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Aluminium foil as best practice – nanolayers provide stability

Nanoscale coatings can perform miracles. They enable easier cleaning processes, reduce reflectance or provide protection against external influences. In the production of functional materials, they represent a tried and tested way of using sensitive substances in hazardous environments.

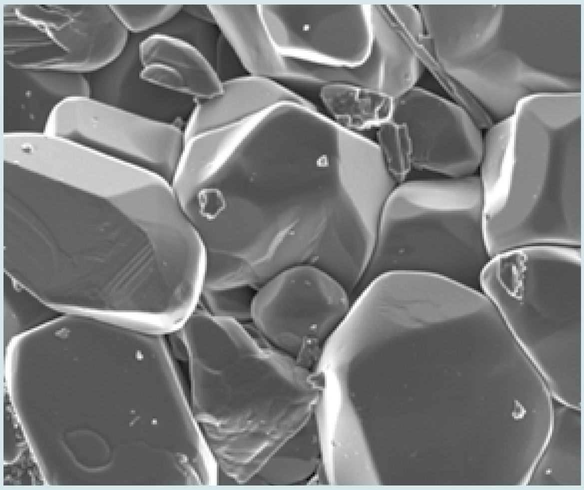

Image produced with a scanning electron microscope, showing uncoated phosphor particles, approx. 3.5 µm in size, of the UV phosphor YPO_4:Bi

Aluminium is one of the basest metals in existence, and yet it is used in every household as foil with one-tenth of the thickness of a human hair. It would be logical to expect aluminium – like many other base metals – to oxidize immediately and completely upon contact with air and water and to be converted into aluminium compounds containing oxygen, such as oxide. However, it would not then be possible to use it as foil, because the oxide is brittle and hard, and the foil would crumble. The reason for the unexpectedly high stability of aluminium in the air is to be found in the nanoworld.

Aluminium protects itself against the oxidization process. An oxide layer forms onto the surface, as expected. But this layer is so perfect and so impermeable that water and air cannot penetrate to the non-oxidized metal underneath it. As a result, the conversion of the metal into its oxygen-containing compounds is restricted to a nanometre thick layer onto the surface. If this oxide layer is produced technically on aluminium components, under controlled conditions, this is known as anodization.

Application in discharge lamps

The high stability of aluminium oxide is the reason why it is also used for coating processes in the production of optical functional materials. The "Tailored Optical Materials" team led by Prof. Dr. Thomas Jüstel is carrying out research not only towards novel compounds, but also on the adaptation of familiar materials for large-scale technical use.

This includes not only the optimization of the physical material properties such as particle size, but also coating processes to improve the in- and out-coupling of radiation, as well as the stability. Just like magnesium oxide or silicon dioxide, aluminium oxide also has a very large optical band gap, which means it is transparent for short-wave, high-energy radiation such as is used in discharge lamps. The basis of any discharge lamp, which includes energy-saving lamps, is the conversion of electrical energy into high-energy (ultraviolet) photons.

So far, mercury has been widely used for this, with newer developments opting for xenon. In order to produce visible light for lighting purposes, these high-energy ultraviolet photons have to be converted into blue, green or red photons. This is precisely the task that phosphors perform.

Discharge lamps for disinfection

Discharge lamps are widely applied for water disinfection purposes. Herein, the phosphors used generate ultraviolet radiation with wavelengths, which are optimized for inactivating micro-organisms such as Escherichia coli bacteria. To ensure a long service life for the light source, these phosphors must be stable under the conditions existing inside the lamp.

The molecules or ions produced for the discharging process – as well as the photons they emit – are so aggressive that they can damage or even destroy the phosphors. Processes are necessary for coat-

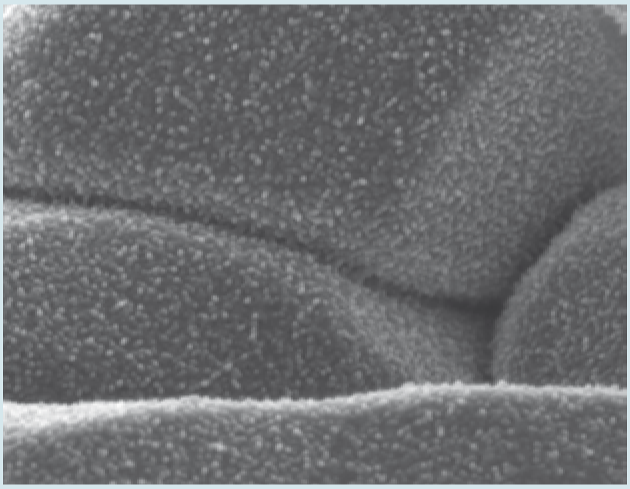

Image produced with a scanning electron microscope, showing phosphor particles approx. 3.5 µm in size and coated with oxidic nanoparticles of the UV phosphor YPO4:Bi

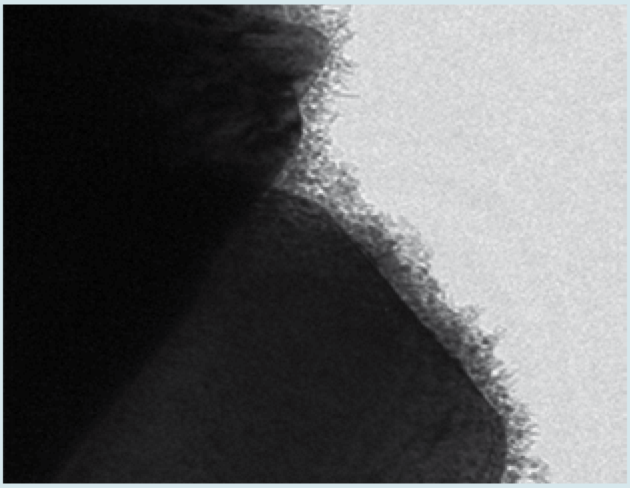

Image produced with a transmission electron microscope, showing phosphor particles approx. 3.5 µm in size and coated with oxidic nanoparticles of the UV phosphor YPO4:Bi

ing the individual phosphor particles in the powder layer, which are also suitable for the manufacture of mass products such as discharge lamps – and the only methods which can then be considered are solvent-based ones.

Packing materials in tight

In water-free ethanol or isopropyl, for example, it is possible to encapsulate moisture-sensitive materials by applying a nanometre-thin layer of an inert oxide in such a way that these materials can be used without any difficulty. The big difficulty is in making these layers so tight that the inside of each particle is completely shielded. Even the smallest pinhole would lead sooner or later to the disintegration of sensitive material.

What is known about xenon, for example, is that it certainly reacts with some of the stable oxidic phosphors, although it was long assumed that noble gases such as xenon do not form any compounds at all. By applying what is, in comparison with xenon, a truly stable protective layer made of magnesium oxide or aluminium oxide, the Jüstel team has succeeded in markedly extending the life of the phosphors in low-pressure xenon discharge lamps. The normal radiation yield for uncoated phosphors after one thousand hours of operation is 30 percent of the initial value, but it has been possible to achieve increases of 70 to 80 percent as a result of such protective coating.

Tailored Optical Materials

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Thin, thinner, two-dimensional!

Graphene & Co: new types of material with exotic properties

If a note-block is halved again and again, all that remains in the end is a single sheet of paper. Solids, which are structured in layers, behave in exactly the same way: repeated splitting results in an ever thinner film, which then ultimately consists of just one atomic layer, giving it a density of less than one nanometre.

The length and breadth of such two-dimensional material are millions of times larger. The prototype here is graphene, an ultra-thin film of carbon. The "Physics of 2D Materials" team, led by Prof. Dr. Carsten Busse, prepares and characterizes such films.

Crazy physics

2D materials show very particular physical properties. The electrons in graphene, for example, move at a constant speed – regardless of their energy – and thus behave just like massless photons (light particles). This and other effects are also very interesting with a view to applications: "Nowadays, every physicist knows graphene because of its technological potential – and because of crazy Dirac physics!" says Wouter Jolie, a PhD student in the team. The wide range of possible applications have led to the EU starting its biggest research initiative ever here with the "Graphene Flagship".

The special crystalline structure necessary for the formation of 2D material can be recognized by the three-dimensional starting materials (to the extent that these exist at all). In the two (currently) most important representatives of this class of materials – graphene and individual molybdenum disulphide films – these are the minerals graphite and molybdenite. Because of their layered structure, individual levels of this material can be very easily moved against each other, as a result of which they can be used for example as a dry lubricant. "Every mechanic knows Molykote, with its most important component MoS2," says Carsten Busse. In the case of graphite, this property is used in everyday pencils. A line drawn with a pencil is nothing other than a line consisting of pieces of graphene. This means that it is possible – almost as if by magic – to create graphene by simply drawing a structure (as long as a pencil is used for the purpose ...)

At the Institute for Material Physics, the preparation is undertaken in alternative ways. Under highly controlled conditions, monoatomic films are deposited on extremely clean metallic surfaces (the substrate) with a defined crystalline structure of the surface. Graphene is produced through a catalytic process in which a gaseous hydrocarbon decomposes into carbon and hydrogen over a hot, chemically active metallic surface. To produce ultrathin MoS2 films, molybdenum is evaporated out of a red-hot rod, and then sulphur is added to the metallic surface through the reaction of the molybdenum atoms with hydrogen sulphide.

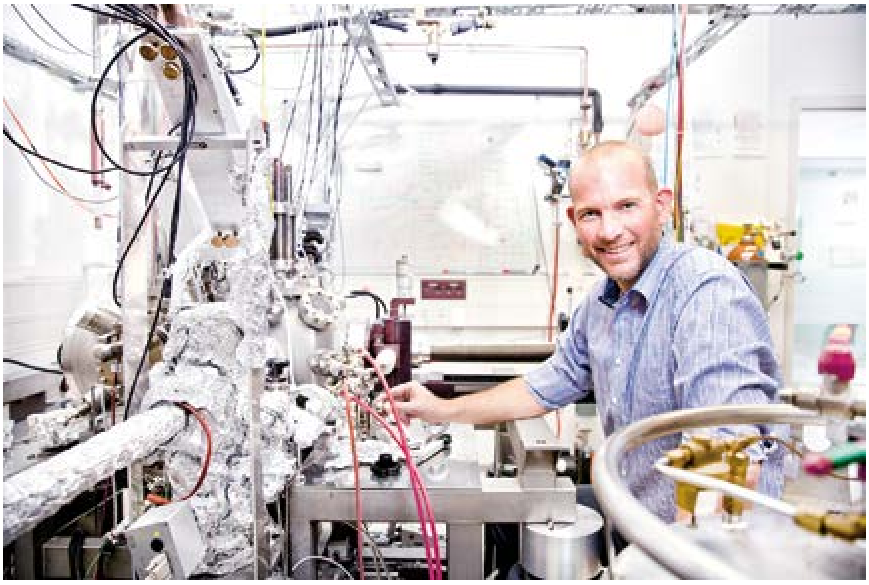
For the characterization process, the scanning tunnel microscope (STM) is used, with which individual atoms of the samples can be made visible. "Exploring the world of atoms with this device is like exploring the surfaces of distant planets," says Dany Dombrowski, who is working on nanostructures from graphene and MoS2 in her doctoral thesis.

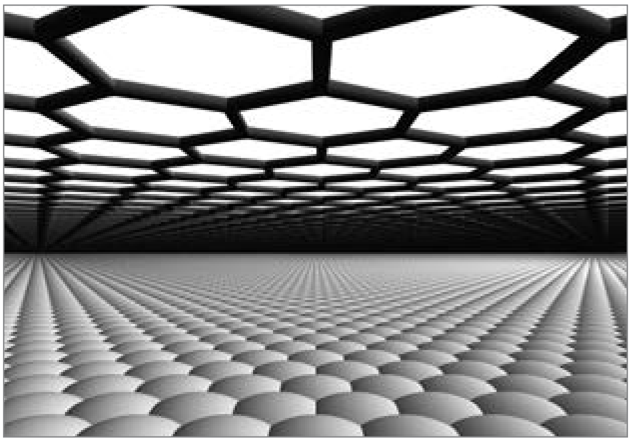
A diamond in Oxfordshire

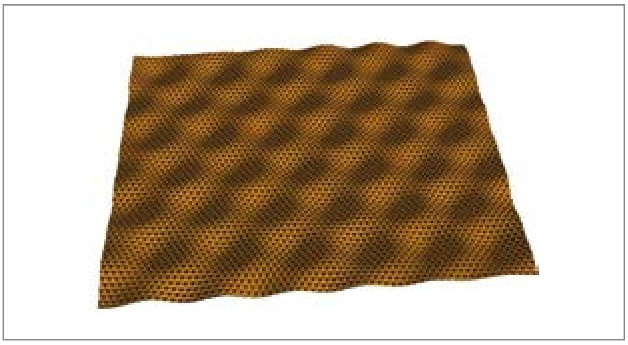
The team also makes use of large research institutes in other countries. Over the past few years this has been primarily "Diamond", the national synchrotron light source centre in Oxfordshire, England. Here, electrons are accelerated almost up to the speed of light and they then give off X-rays, which are needed for any precision measuring of structures. "As a result," says Carsten Busse, "we have been able to define exactly the binding distances between 2D materials and their substrates, down to one billionth of a millimetre – as well as separately, by chemical species.

Caio Silva, currently a scholarship holder in the Brazilian "Ciência sem fronteiras" programme and a member of the team, adds, "Investigating nanomaterials with synchrotron radiation is really fascinating because you can learn a great deal from the interaction between light and material."

The number of synthesized 2D materials is currently growing at a tremendous speed – but the







Graphene film seen through a scanning tunnel microscope. The wavy structure is caused by the Moiré effect between graphenes and the metallic surface below.

total number of materials predicted in theory has nowhere near been reached. "There is great potential in the combination of materials," says Carsten Busse. "The required properties of the individual components can be united in one system – even bringing about entirely new effects."

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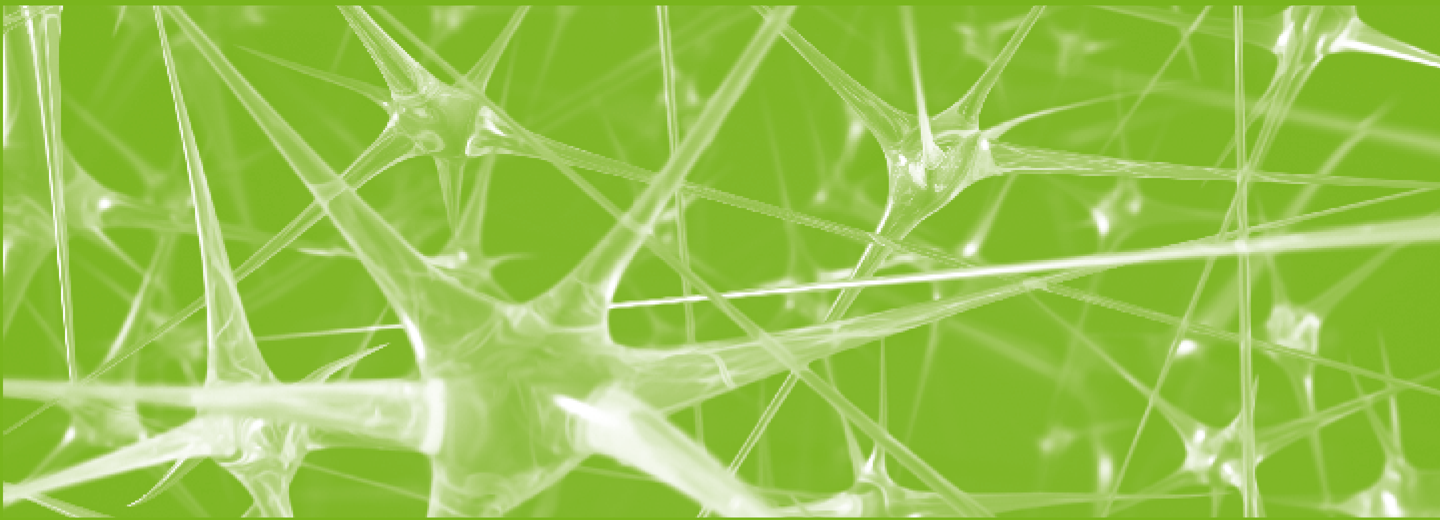
Nanobiomedicine

The application of concepts from nanotechnology in medicine combines two large, interdisciplinary fields of research which have unparalleled social and economic potential. Nanobiomedicine makes use of the achievements made in both fields of research, the common basis of both being the investigation into specific properties on the molecular level. With the aid of local probes and molecular imaging techniques, surfaces and interface properties on a nanometre scale can be characterized at given measuring points, while the use of chemical methods enables surfaces to be modified and addressed in a controlled way.

Examples of this are new types of concepts for the targeted transport of active agents, the optimization of biocompatibility and neuroprosthetic applications. While nanobiomedicine restricts itself to the application of concepts from nanotechnology for medical purposes, nanobiotechnology comprises the entire range of basic research in the nanometre cosmos of biological systems. This includes the examination of plants.

The importance of nanobioanalytics and nanobiomedicine played a major role in setting up the Alliance for Science, which was undertaken by the City of Münster, the University of Münster and Münster University of Applied Sciences. Working in teams, representatives of Münster



City Marketing, the University, the University Hospital, the University of Applied Sciences, the Max Planck Institute of Molecular Biology and various companies involved drew up strategies for making the opportunities provided by this technology better known and for publicizing new medical preventive measures. The impressive results of this strategic alliance can be found on the Internet at www.allianzfuerwissenschaft.de.

The next chapter presents projects from the field of basic research, as well as practical medical applications, which illustrate not only the importance of nanobiomedicine, but also the opportunities and challenges it presents.

Flashes of light make markers and antibodies visible

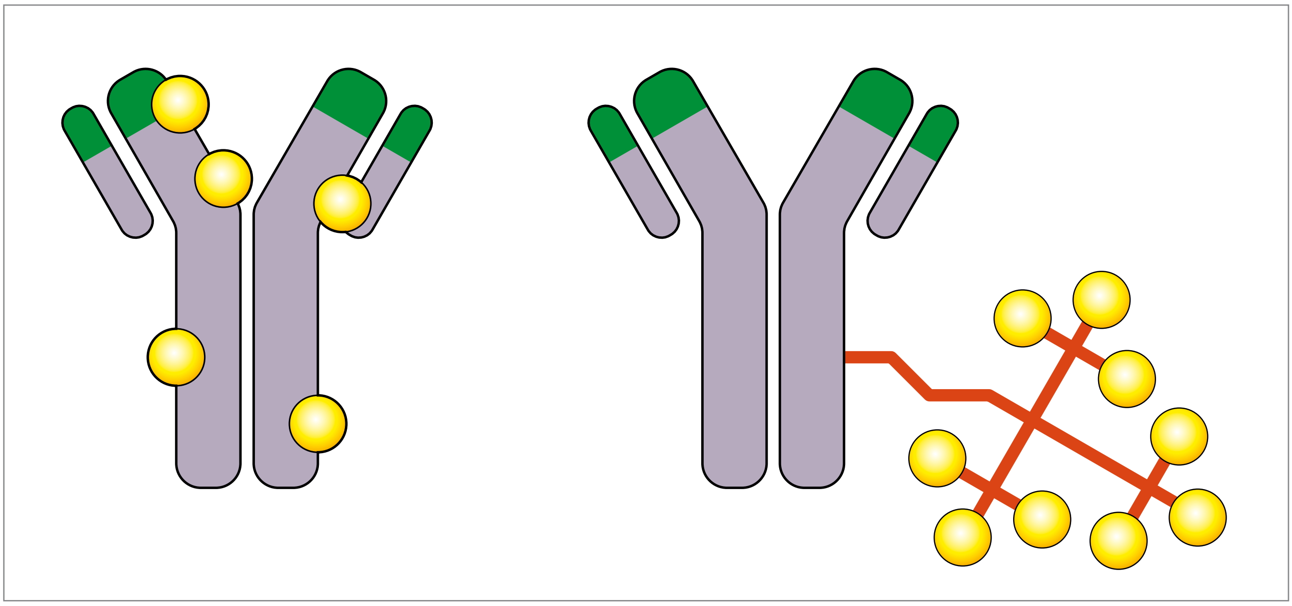
Luminartis' important breakthrough in special labels for use in bioanalytics

The Luminartis GmbH Company specializes in the development and production of high-performance fluorescence dyes (or labels). These substances are needed in bioanalytics, for example in immunofluorescence or in so-called in-vivo imaging. The labels are coupled to antibodies or suitable marker substances, thus forming conjugates, which are brought into contact with cells, for example. The antibody "recognizes" a specific cell structure or a tumour cell and becomes visible when it is irradiated with light which has a certain wavelength. The fluorescence dye emits a characteristic coloured light and reveals information on the location and quantity of the marked substance.

In the case of in-vivo imaging, conjugates are implanted in the living animal in order to recognize tumours or inflammatory processes and make them visible. The principle being used here is that long-wave light, invisible to the human eye, can penetrate through the tissue a few centimetres and, in doing so, stimulate fluorescence dyes. The aim is for this non-invasive diagnostic process, which was initially established for mice and rats, to be used later on humans. The first hand-scanners for the early recognition of rheumatism are already commercially available and are being used in large hospitals. Although the market currently offers a large number of mostly organic fluorescence dyes, their use in practice is often limited by a number of factors – for example, a lack of fluorescence, unwanted interactions with the biomolecule or too high a background signal.

Exceptionally biocompatible

The team of researchers at Luminartis has developed a new kind of chemical process to improve the water-solubility of organic compounds. This makes it possible to get fluorescence dyes with exceptionally high biocompatibility, which means that they are more compatible for the tissue being examined because the properties of the coupled biomolecule are hardly impaired at all. Nor does the dye show any unwanted effects. The process at work here is a generic one that can be transferred to numerous other dyes, sensor surfaces or nanoparticles. These new dyes are sold under the trade name Oyster. Biocompatibility not only plays an important role in the interaction between fluorophore and antibody, but it can also determine whether certain conjugates in the body cyclize freely and are then discharged through the bladder or accumulate in the liver. Working together with teams of medical research-



Conventional coupling of fluorophores (left) and an alternative coupling method with nanostructured dye oligomers.

ers, it was shown that the Oyster dyes are particularly suitable for in-vivo imaging.

One important parameter for fluorescence dyes is the label grade. This is the molar ratio of fluorophore to the biomolecule. Commercial antibody conjugates often use moderately water-soluble fluorescein (FITC) or rhodamine (TRITC). They are available with a label grade of 0.5 to 2. With more soluble dyes, more dyes can be accommodated per antibody without the functionality suffering. The result is a higher luminosity of the conjugates.

Label grade characterizes quality

One problem remains, however. Despite the high biocompatibility, the functionality of an antibody can suffer as a result of covalently bonded dyes. This is the case when a fluorophore happens to be bonded in the vicinity of the antigen binding site (diagram, left). The biocompatible dyes gave rise to the nanostructured fluorescence dyes. These are small hydrophilic supports, which contain a defined number of fluorescence dyes and deliberately dock on to a certain position of an antibody or another biomolecule. Just a few binding sites are sufficient to accommodate discrete dye packages (diagram, right). The result is an optimum compromise between a minimal influencing of the antibody and a label grade, which is as high as possible.

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A deep look inside the tangle of synapses

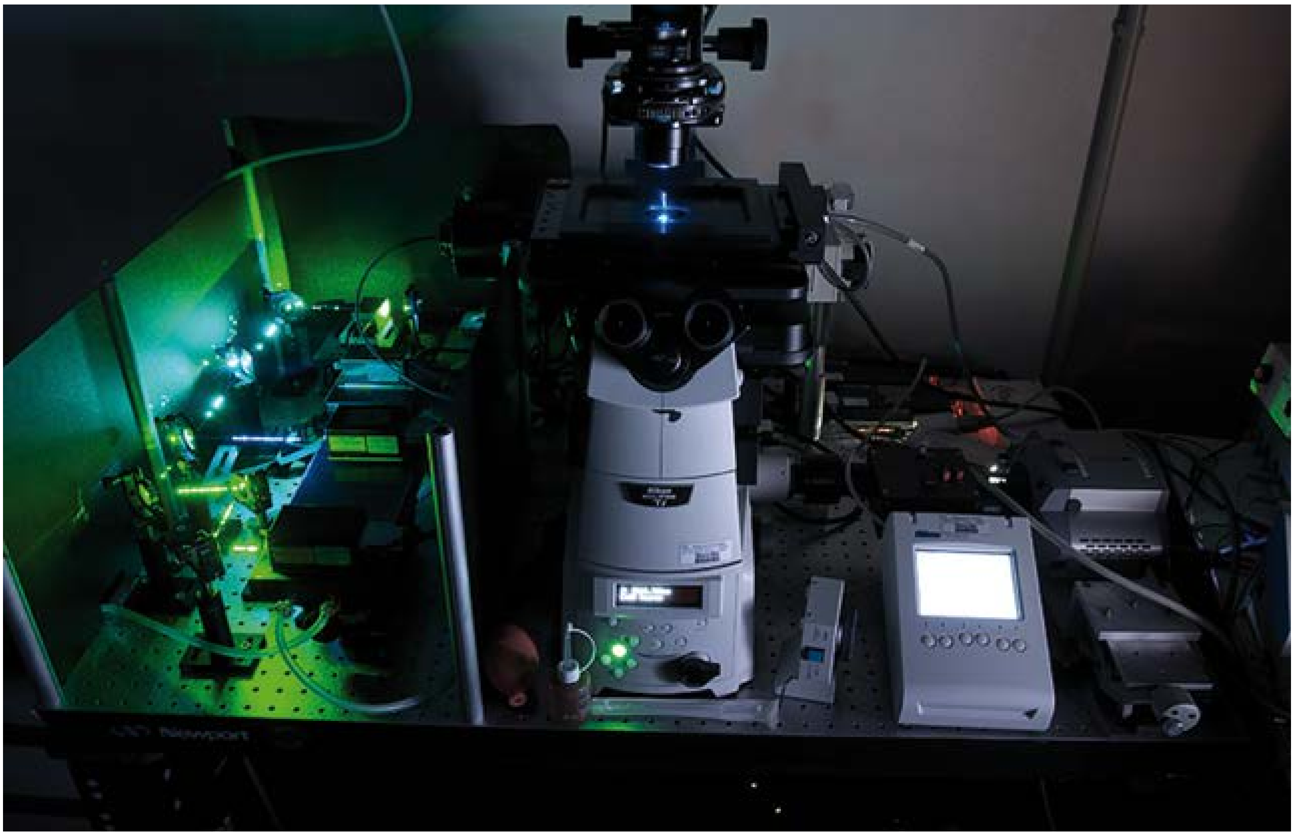
Special microscopes provide unexpectedly detailed images of the inner structure of biological cells

Living cells are hidden to the human eye: these basic components of our body, our skin, our organs, or brain, are simply too small. In order to research into them, special microscopes and methods such as fluorescence are needed. This is the focus of the work being done by the team of researchers led by Prof. Dr. Jürgen Klingauf. Among the things they are analysing are the signalling pathways and transport processes in living nerve cells. At the synapse, the point of contact between two nerve cells, so-called messenger substances (neurotransmitters) are released within a short space of time.

They come from small bubbles (vesicles) located before the synapses and are stimulated by inflowing calcium ions to merge with the plasma membrane. In order to maintain the function of the synapses, the number of vesicles ready for release must be continuously replenished. This happens by means of an inverted process, endocytosis. The researchers use various microscopy techniques to analyse this process, such as fluorescence photoactivation localization microscopy (FPALM), stochastic optical reconstruction microscopy (STORM), 4Pi microscopy and total internal reflection microscopy.

Resolution of just a few nanometres

These permit resolutions of just a few nanometres, thus making it possible to look deep inside the chemistry and biology taking place inside cells. The special microscopes are available to the University Hospital and the University of Münster as part of the "Fluorescence Microscopy Facility Münster (FM)2", an imaging facility. As a result of unavoidable diffraction effects, resolutions in optical microscopy are limited to around 200 nanometres (one five-thousandth of a millimetre). This is not sufficient, however, to depict much more detailed structures within the cell. FPALM and STORM are two closely related techniques which make it possi-



ble to get round this limitation on resolutions. This happens by using special switchable fluorescence dyes. As a result, the dyed structure is never entirely visible – only ever individual dye molecules. These can, however, be localized with an accuracy ten to fifty times higher than the resolution offered by the microscope. The switchability of the dyes allows all the dye molecules to be depicted one after another in order to determine their position and, ultimately, reconstruct the structure to be investigated with an accuracy of a few nanometres (millionths of one millimetre). This technology was awarded the Nobel Prize for Chemistry in 2014.

Two nanoscopes constructed

Prof. Dr. Klingauf's team of researchers have constructed two such "nanoscopes" which they can use to make FPALM and STORM measurements. One of the devices is based on a commercial epifluorescence microscope. A variety of additional pieces of technology make it possible to determine not only the lateral but also the vertical position of the dye molecules, and thus to produce 3D images. The second device is a special construction with two lenses, through which almost the entire fluorescent light which the sample emits can be detected – which again substantially increases the accuracy in determining the positions of the dye molecules, and thus also the accuracy of the image reconstruction.

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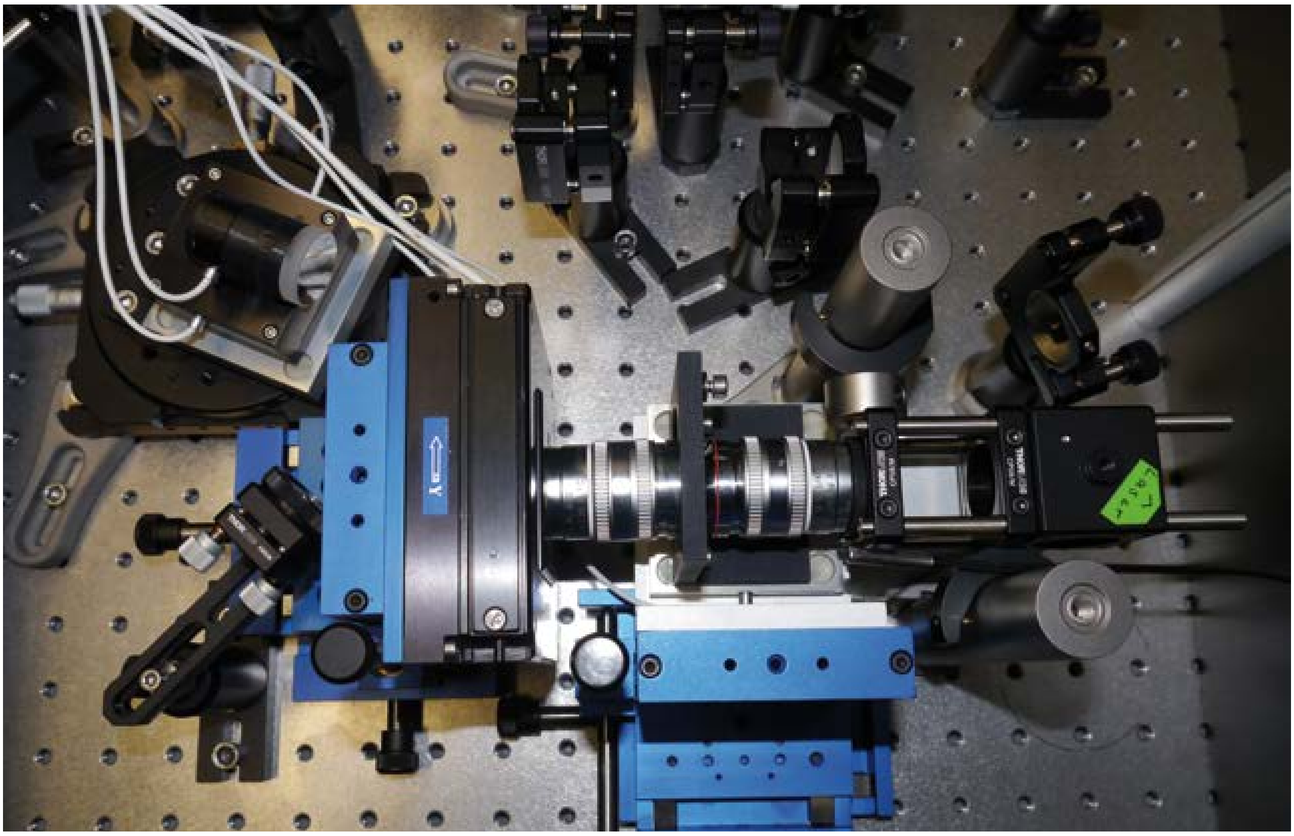

A vision of medicine becomes reality

Nanoparticles can carry pharmaceutical substances and concentrate them in diseased cells

Special nanoparticles, acting as Trojan horses for pharmaceutical substances, are opening up new perspectives in the pharmacological treatment of diseases. A team led by Prof. Dr. Klaus Langer at the Institute of Pharmaceutical Technology and Biopharmacy at the University of Münster is looking for ways of packaging the substances and targeting diseased cells in which to concentrate them. A hundred years ago, scientist Paul Ehrlich had a vision of producing "magic bullets" for the treatment of cancer. What he meant was pharmaceutical substances which only had an effect on cancer cells and left healthy cells unharmed. Ehrlich assumed that every cell surface was equipped with specific receptors, into which certain biomolecules fit like a key fits a lock. Although this principle proved its worth in fighting bacteria, Ehrlich made no progress in treating cancer. Developments in medical nanotechnology have now enabled scientists to manipulate particles which are much smaller than human cells. Ehrlich's vision can now become reality.

How drug targeting works

How should pharmaceutical substances be packaged so that, as drugs, they have the desired effect in the body? The traditional ways of administering them – as tablets, capsules or ointments – influence the release of the active substances they contain but have no effect on how they are distributed inside the body. The doctor chooses the form which promises optimum availability and, therefore, the best possible effect in the body. In the case of tablets or ointments, however, only a fraction of the substance administered reaches its intended destination. The rest spreads out over the entire body in an uncontrolled fashion and can cause unwanted side-effects which often have a very adverse effect on the quality of life of the patient concerned – for example, in chemotherapy to combat tumours. It is for this reason that pharmaceutical research has long been looking for a suitable transport system for taking the active substance to precisely where the disease is – to the tumour. This is called drug targeting.

The researchers in Prof. Dr. Langer's team are taking a promising approach to concentrating pharmaceutical substances in the desired target tissue. They use nanoparticles, which bind the substances to themselves and transport them through the body. Because they are so small, they can concentrate the bonded substance in organs, tissues or diseased parts of the body. This type of drug targeting has shown itself to be highly successful.

Nanoparticles transport active substances

Nanotechnologists are now able to tailor the structures of particles, which move in an order of magnitude in which molecular processes in a cell occur. The nanoparticles can be produced in a uniform size and in a technically reproducible way. In drug targeting, the aim is to concentrate the pharmaceutical substance transported in specific, or targeted, parts of the body which are otherwise difficult or even impossible to access. In doing so, the nanoparticles have to be protected from being attacked or destroyed by the body's own health police – phagocytes, also known as scavenger cells. The surface of the nanoparticles can be fashioned in such a way that they remain unnoticed and escape these attacks. Then there is no longer anything to hold them up and prevent their stay in the target tissue. If they spend enough time in the body, the nanoparticles can locate the different intercellular spaces in healthy and diseased tissue. This is used to concentrate pharmaceutical substances in tumours. This is not, however, the same thing as an effective concentration in a single tumour cell. If the nanoparticles are equipped with special recognition

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domains such as antibodies, they can dock onto certain cell types. In this way, the active substance accumulates in the cell.

Success with breast cancer

For some years now, the researchers in Klaus Langer's team have been researching into and developing such intelligent particle systems, which actively recognize tumour cells. These systems are based on biodegradable proteins or synthetic polymers. A variety of active substances can be embedded in the particle matrix. The surface of the nanoparticles can be modified using methods from protein chemistry in which they are equipped with specific ligands, depending on the target tissue. In this way, for example, a specific concentration of nanoparticles can be attained in breast cancer cells, which carry the antigen HER2 on their surface. Only nanoparticles, which are charged with a pharmaceutical substance and at the same time carry the appropriate ligand on their surface, will manage to concentrate and release the active substance in the breast cancer cells. If the ligands are exchanged, the nanoparticles can be tailored for other applications.

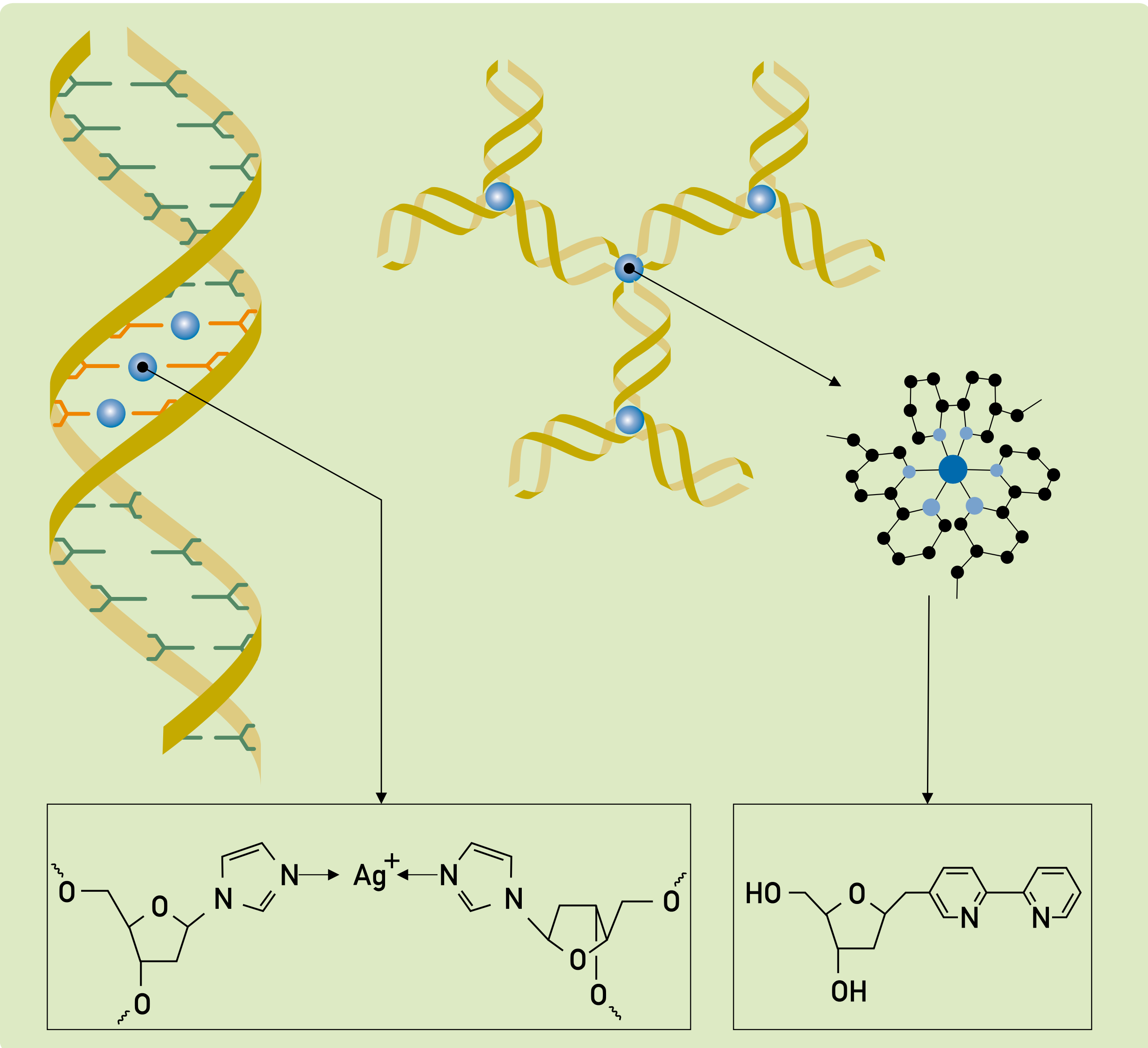
In another project, for example, the particle surface was equipped with apolipoprotein E (ApoE) as the ligand. ApoE is a protein which the body uses for transporting cholesterol and fats into the brain via the bloodstream. In experiments with animals, these particles were able to transport a painkiller across the blood-brain barrier. Without such a transport system, this physiological barrier cannot be overcome. The results give rise to the hope that brain tumours may soon be treatable using medication. So far, the traditional methods of administering pharmaceutical substances have failed. The scientific work carried out by the team on establishing new drug targeting concepts is being financed through funding from the Federal Ministry of Research for the NanoGene, BioTraP for CCC and MINAC projects.

The team led by Prof. Dr. Langer

DNA as a model for new synthetics

Nucleic acids modified with metal ions make molecular nanoprobes and special polymers possible

Research into the carrier of genetic information (DNA) is making huge progress. The enormous molecule is a so-called nucleic acid and it forms the basis of all life on Earth – from bacteria and plants to humans. In the course of millions of years of evolution, nature has never ceased to refine and optimize it. By implanting metal ions, researchers are trying to change the properties of nucleic acids in order to synthesize molecules with completely new properties. In the team led by Prof. Dr. Jens Müller, the metal ions are implanted very precisely in the complicated chemical structure of nucleic acid. The researchers analyse how its properties change as a result and what new applications this gives rise to. If nucleic acids are modified with artificial, metal-mediated base pairs, the result is a biologically inspired, synthetic polymer. The production



Two possible ways of functionalizing nucleic acids with metal ions. Left: DNA duplex with metal-mediated base pairs; right: section of a nanostructured DNA metal aggregate. The metal ions are shown in blue.

Scientists use the rules of evolution for their research work.

of the synthetic DNA molecules is undertaken using a synthesis robot.

The robot assembles the polymers

The chemical components needed (monomers) are synthesized by the researchers and characterized in detail. The robot assembles the polymers from the easily accessible monomers in a fast, automated process. This results in a large number of different molecules with variable properties. Intensive research into these new types of compound is being put on a broad base through collaborations with researchers in Amsterdam, Zurich and elsewhere. Over the past few years, there have been many examples providing evidence of the synthesis of these compounds. Prof. Dr. Müller and his team now want to devote themselves more to analysing possible applications. In the Collaborate Research Centre "Synergetic Effects in Chemistry", for example, they are looking at the question of the extent to which the metal ions in DNA influence the charge transfer through the nucleic acid. An application as a nanoprobe for metal ions is just as conceivable as the production of nanostructured DNA aggregates with cavities of variable sizes.

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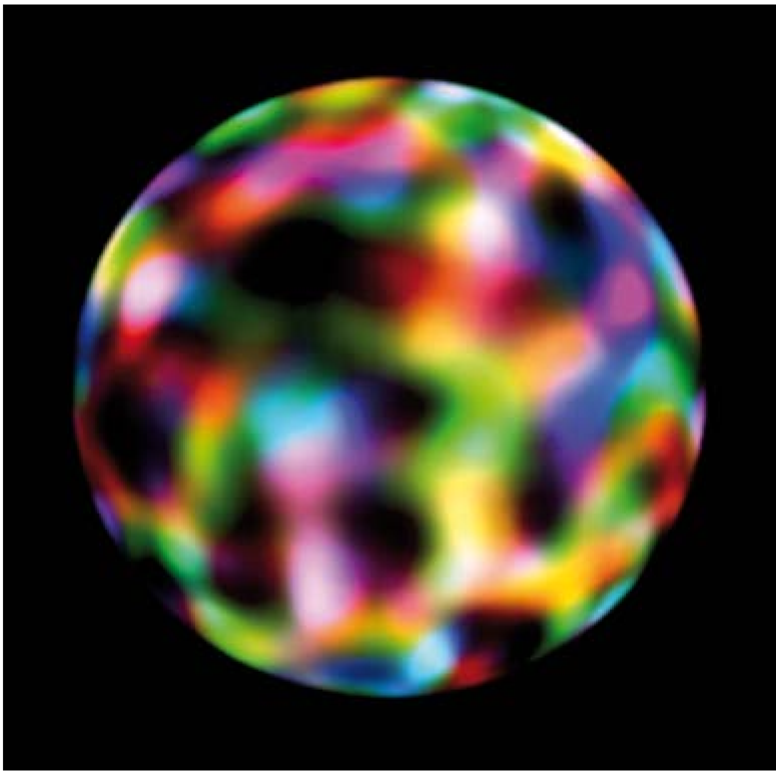
The cell as organized chaos

In a cell, highly dynamic processes are constantly being executed which are precisely regulated and coordinated. Roland Wedlich-Söldner and his team at the Institute of Cell Dynamics and Imaging are studying how cells maintain such a tight organization. These studies are highly relevant for many areas of modern biosciences, not least to support the development and application of synthetic living systems in the micro- and nano-ranges.



Dynamic support. The cytoskeleton consists of a large number of filaments, which are constantly being formed and again destroyed, but which nevertheless provide mechanical stability for the cell. Shown here is the organization of a myosin network in a dog kidney cell. Image diameter corresponds to 40 µm.

At first glance, what seems to prevail in the interior of every cell is impenetrable chaos. Intensive research is required to reveal even partial features of the tight regulation in this dynamic system. Each process in a cell can, and must, occur at the right time, in the right place and to the correct extent.

Wedlich-Söldner and his team want to decode the fundamental biological mechanisms underlying cellular dynamics and pattern formation. Ultimately, everything centres on the question of how a cell manages to execute the numerous processes in its interior with optimal temporal and spatial precision, while not incurring any disruptions from molecular crowding and noise.

The indispensable scaffold

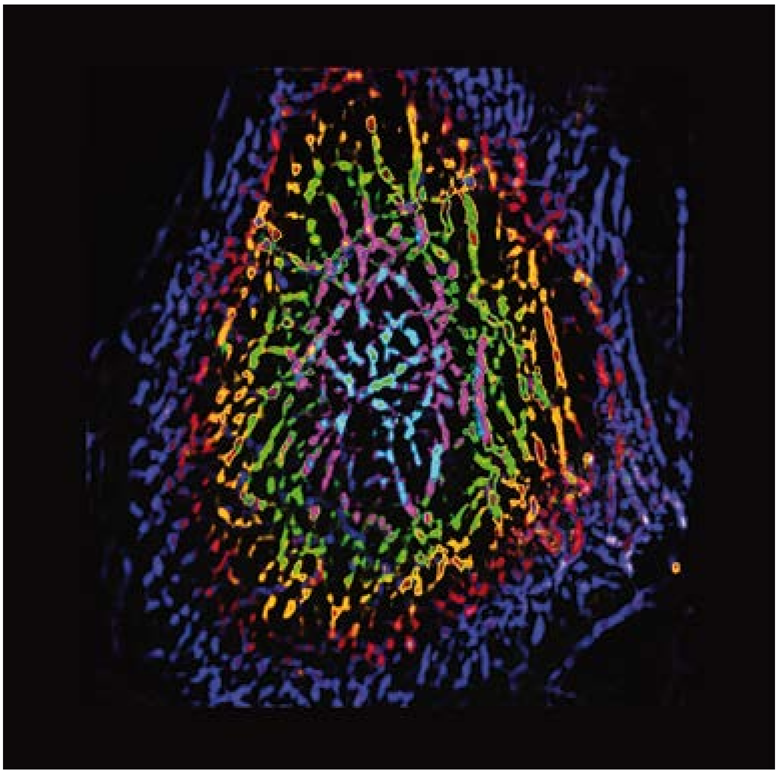
One of the researchers' main areas of focus is the cytoskeleton, an essential component of all higher cells. It is formed from a variety of protein filaments, which, depending on requirements, assemble into flexible bundles and networks that provide cells with shape and mechanical support. The cytoskeleton is also needed for the transport of molecular cargoes that play a role in almost all cellular processes.

One example of this is the process of cell polarization, where a cell loses its symmetrical organization and instead has to orient itself in one direction. When a yeast cell divides, for example, numerous molecules and cellular structures have to be targeted to a defined place, where they support formation of the new bud, out of which the daughter cell will be formed.

In a different project, Wedlich-Söldner's team has been able to show that the cytoskeleton can also serve as an information carrier. In this case, organization of the cytoskeleton changes within just a few seconds as a response to acute cell stress. This occurs for example when a neighbouring cell dies or the cell receives signals during inflammation. Because of this reorganization, however, the cytoskeleton triggers activation of numerous genes, which influence cell behaviour over the course of many hours.

The cinema of the cell

High-tech microscopy is necessary to follow the dynamics of cellular structures and processes in detail and over time in a living cell. Studies of the cell



The cell surface as molecular patchwork. Yeast cells organize their surface into domains which are clearly separated from one another. Image diameter corresponds to 6 µm.

surface are carried out primarily with the aid of special fluorescence microscopy. For this purpose, the Wedlich-Söldner team has set up several high-performance microscopes and established appropriate methods for image analysis.

As a result, the team has been able to show that yeast cells organize their entire surface into numerous so-called domains which are laterally separated from one another and which each contain unique combinations of proteins. This "molecular patchwork" appears to be of central importance for many basic cellular processes: proteins partially or completely lose their function when they are moved to a foreign domain.

Movies, which can be acquired thanks to state-of-the-art microscopy techniques and equipment, generally provide more detailed insights than mere snapshots. They frequently reveal new cellular processes or previously unknown structures that could help to decode living systems – ranging from simple bacteria to entire humans. The basic principles thus revealed can also deliver important models for the development of synthetic cells and complex chemical systems.

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Nanomedicine: opportunities as well as risks

New types of treatment are tested for their tolerance before being used on patients

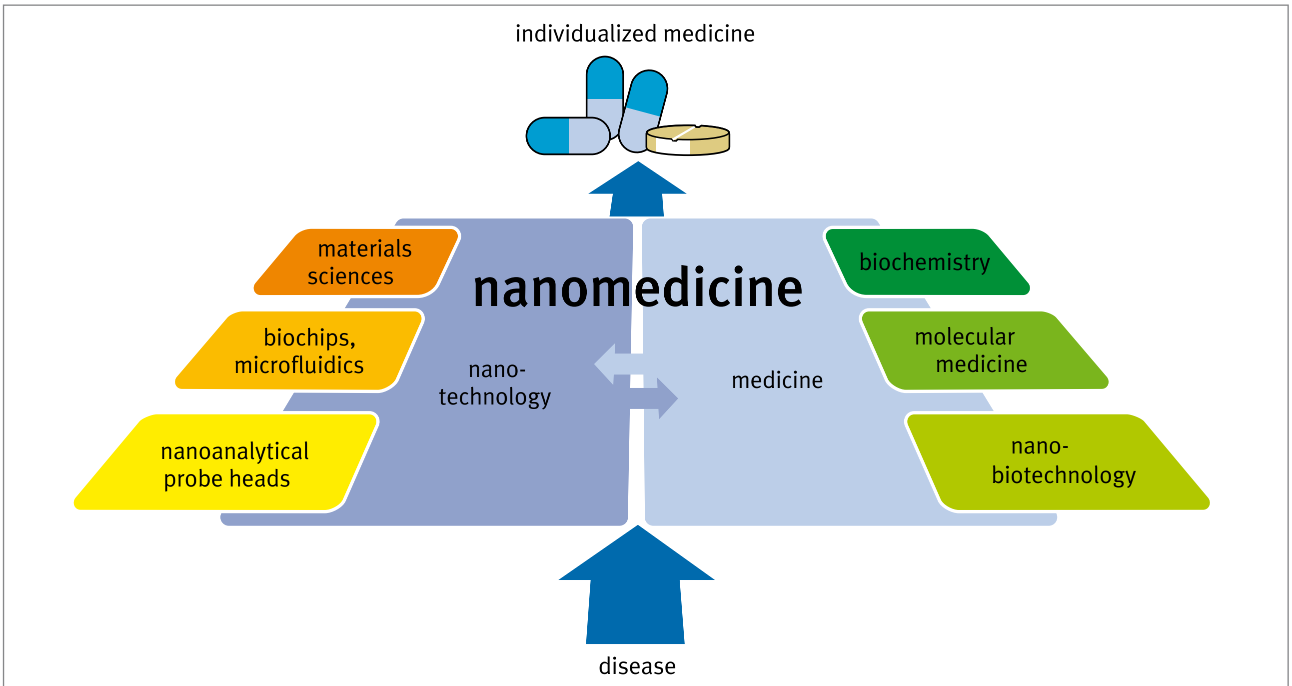
In nanomedicine, research is undertaken on nanotechnological concepts for diagnoses and treatments. The potential is immense. On the other hand, there are reservations as regards the health risks. The team led by Dr. Kristina Riehemann is not only working on nanoanalytical approaches for early diagnoses of diseases. They are also analysing the risks presented by nanoparticles in cells in the immune system and in barrier-forming cells.

Over the past few years, nanotechnological methods in diagnoses and treatments have led to rapid developments in nanomedicine. Analytical tools such as local probes and molecular imaging techniques permit the properties of surfaces and interfaces, as well as their influence on the individual atom or molecule, to be characterized and controlled precisely.

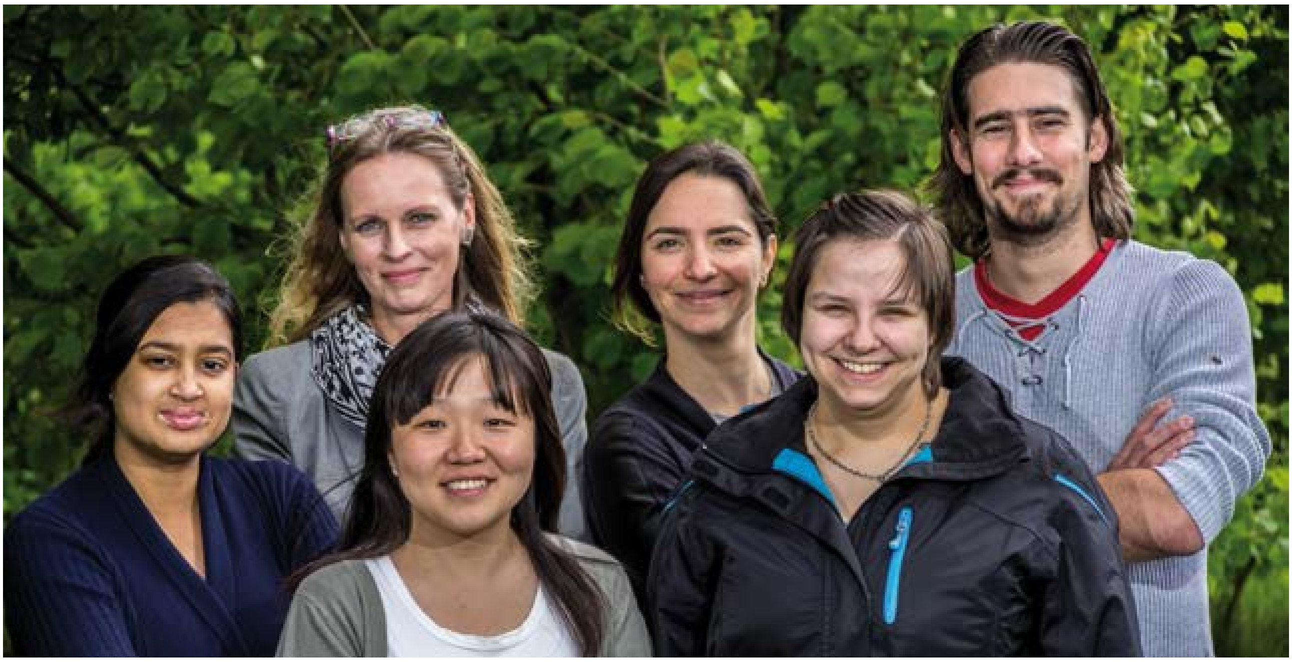
On the other hand, medicine is faced with extremely complex challenges. Because of people's increasing life expectancy, it is possible to recognize particular illnesses which will have considerable socio-economic consequences in the coming years. With the aid of new types of diagnostic concepts, optimized biocompatibility and neuroprosthetic applications, nanomedicine will be in a position to overcome these challenges. It opens up new perspectives which are of enormous interest in the industrial and clinical fields. One thing that will be essential is for the tolerance of nanoparticles and nanostructures in the cell to be guaranteed. Any ecologically harmful effects from all nanomaterials released must also be ruled out.

Wide variety of approaches for diagnostics

One example is the marker-free characterization of tumour cells or of cells in the immune system, which offers a wide variety of possibilities in the field of diagnostics. The elasticity of cells is one parameter for pathological changes. In the course of a disease, the structure of the cytoskeleton, and thus its elasticity, change. This can be measured using a variety of methods. For their analyses, researchers used tumour cell lines as model systems and widened their examinations to include inflammations by analysing healthy and inflamed activated macrophages and by characterizing the differences in the elas-



Overview of the scientific fields covered by nanomedicine



The team led by Dr. Kristina Riehemann

ticity. The cells are manipulated using atomic force microscopy and by means of microfluidic techniques in an electrical octopole. This produces statistically sound data for clinical diagnostics.

Well tolerated or toxic?

The use of nanomaterials entails the risk of the cell tissue becoming inflamed in the case of any intolerance, of an immune reaction leading for example to the rejection of prosthetics or to the development of a growth (cancer). It is known, for example, that fine deposits that occur in hip prosthetics as a result of abrasion can give rise to inflammatory reactions. In addition, particles travel around the body and can cause damage in tissue that is not the original target. If any medical application supported by nanotechnology is to lead to the desired outcome, these risks absolutely must be ruled out.

This means that intensive analyses of the interplay between cells and nanomaterials are necessary. For this purpose, suitable tools and methods are required, among other things, which are suitable for test processes with a high throughput and with uniform standards. One established method for testing biological barriers is to measure the electrical resistance. The researchers in Dr. Riehemann's team have adapted this method to analyses of the toxicity of nanoparticles and have developed it for routine applications (cellZscope in collaboration with the nanoAnalytics company in Münster). In studies of white blood cells in humans, the researchers were able to show that most of the nanoparticles do not cause any inflammatory reactions in direct contact with these cells – at least, not in a test tube. So far, many of the systems examined appear to display only comparatively small, short-term risks. As hidden dangers cannot be ruled out, a systematic assessment of risks is indispensable.

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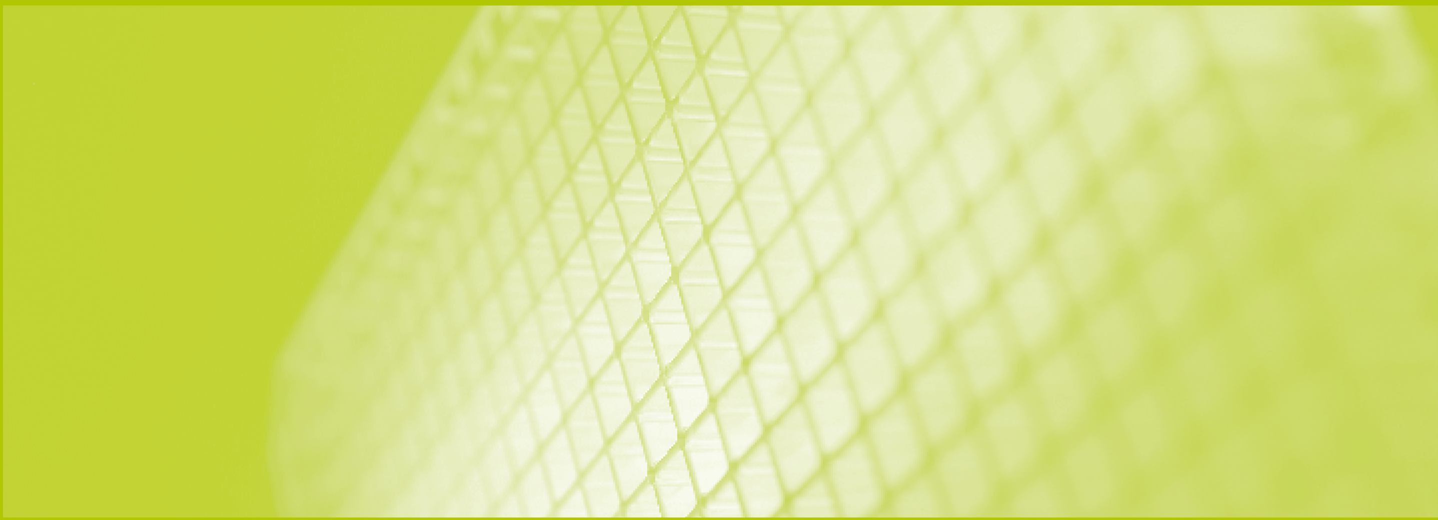
Nanoanalytics and theory

The development of new materials and is determined essentially by their molecular composition and atomic structure. The surfaces are particularly important. Whenever we touch an object in everyday life, we are in contact with its surface – regardless of whether it is a table top, a piece of iron or our clothes.

Therefore, it is just as important to optimize or refine surfaces in practically all areas of our life. These refining processes mostly have several functions: we like car paints, for example, because of their colour or their gloss. At the same time, they protect the sheet metal underneath from corrosion. Clothes are designed to make the wearer look chic and to be permeable to sweat, but also to keep the rain out. Artificial blood vessels and implants should have a long lifetime and be biocompatible – synthetics, by contrast, should be hard but elastic.

This list of examples from everyday life could be extended indefinitely. They all represent the final stage of complex iterative development and optimization processes in which a major role is played by nanoanalytics, which comprises microscopic and spectroscopic techniques, some with molecular and atomic resolutions.

Overall, nanoanalytics allows atomic structures, electrical, magnetic and optical properties and, in the end, also transport properties to be analysed, for example regarding their electronic or ionic conductivities, or their stimulatability through external influences such as light, electric voltage or matter from the environment.



Any specific development of new materials, components, sensors and pharmaceutical products can only succeed through a knowledge of these interrelationships on a scale of their components, i.e. of molecules and atoms. This is why nanoanalytics play such an important role within the entire spectrum of nanotechnologies. The range of applications is exceptionally large. All important technologies need analytics and its theoretical foundation.

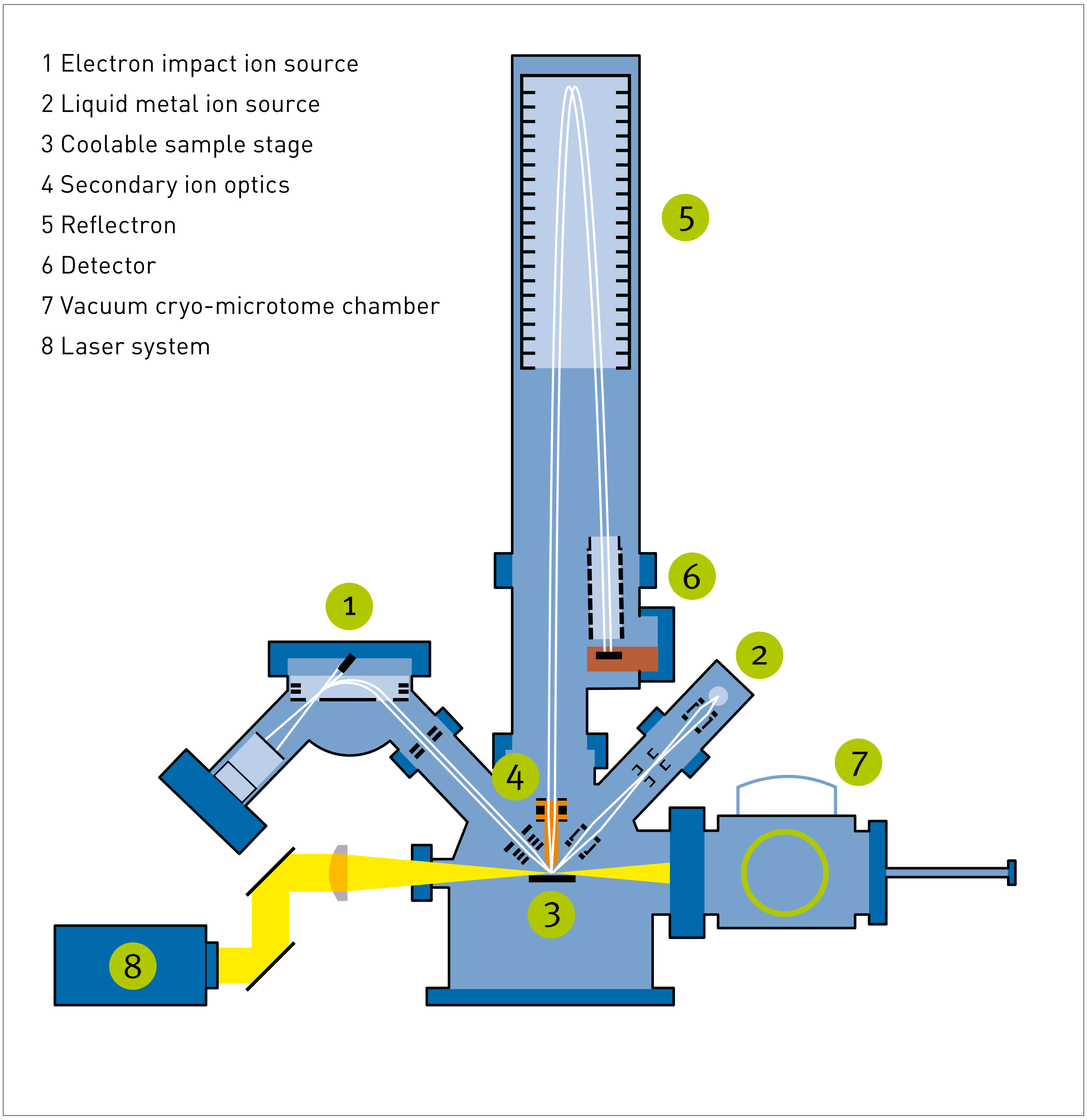
Physical nanoanalytics has a special status in Münster – and a long tradition. Münster has nanoanalytical methods which are not available at other German universities in this scope and degree of specialization. The following pages show some examples. The measurement data from the analytical equipment and models require extra theoretical interpretation. At the same time, theoretical considerations produce important ideas for special analyses, as well as pointers to measurable effects which had not been recognized or noticed before. This is why any successful research in the field of nanoanalytics requires intensive collaboration with groups involved in theoretical aspects.

Looking for the needle in the haystack

Modern mass spectrometry techniques can detect atoms and molecules and probe chemical structures

In order to understand the important properties of materials, one needs to study how they are put together chemically. For material properties, both the atomic structures and the interactions between atoms play an important role. In this research, the inorganic and organic constituents of samples are characterized down to individual atoms.

In the investigation of nanoscale samples, there are three central questions to be answered: 1. What elements, isotopes, molecules or functional groups are present in the samples? 2. What are their con-



Combined Kryo analyser, an in-house development of Münster physicists centrations? 3. How are these constituents arranged and connected on the surface and as a function of depth?

The team led by Professor Heinrich Arlinghaus, at the Institute of Physics of the University of Münster, is bringing state-of-the-art technology to bear on the investigation of unknown substances. One example is time-of-flight secondary ion mass spectrometry (ToF-SIMS), in which the surface of a solid sample is bombarded with electrically charged atoms, i.e. ions.

These ions knock atomic or molecular material out of the topmost layer of the sample, a process which physicists call secondary particle emission. These emissions consist of both neutral and charged particles, from both elemental and molecular species. Electrically charged secondary particles can be detected using the ToF-SIMS equipment. Usually, the charged particles form only a small proportion of the secondary particles emitted, which limits the sensitivity of this method.

This is why researchers turn to a second process: laser secondary neutral mass spectrometry (Laser-SNMS). In Laser-SNMS, the neutral particles emitted are subsequently excited with a laser to form ions. This method requires a clear understanding of the excitation processes in order to correctly interpret the results from the post-ionization. This is because, in the nano-world of atoms and molecules, many different types of fragmentation and rearrangements are possible and the correct interpretation of the results is not always obvious.

State-of-the-art technology

By bombarding the sample with a focused and rastered ion beam, an image can be obtained showing the two-dimensional distribution of chemical species on the sample surface. The researchers gain insights into the arrangement of the atoms and molecules in the outermost sample layer, which plays a significant role in determining many properties of materials. If an additional sputter ion source is used, layer after layer can be removed from the sample, thus revealing the chemical composition and structure in the interior of the sample. This is known as a depth profile. If all this information is put together, the result is an image showing the 3-dimensional distribution of chemicals within the sample.

The Münster physicists have developed a combination ToF-SIMS / Laser-SNMS instrument, which is unique worldwide and in which samples can be analysed at very low temperatures. This cryo-analysis instrument, with integrated cryo-microtome, makes it possible to work on frozen biological samples, in vacuum, so that their three-dimensional structure can be determined. This state-of-the-art technique has been used, for example, to detect, localize and quantify the active ingredients of pharmaceuticals in cells and tissue. It has also been used to detect nanoparticles in cells and measure toxic compounds in tiny particles from air pollution.

Deep-frozen biosamples

ToF-SIMS and Laser-SNMS have provided answers to many questions in nanoanalytics, nanoelectronics, research into the way pharmacological substances work, and the development of biosensor chips to identify DNA and protein sequences. Applications range from environmental research and paleoceanography to the characterization of roller bearings and clutches, whose surfaces are subjected to rigorous demands. Isotopes have been measured in frozen plankton for climate research. Prof. Dr. Arlinghaus' team have developed new methods to locate and quantify pharmacological substances for destroying tumours in affected cells. For this purpose, the researchers took a detailed look at tiny samples from tumour tissue in laboratory animals.

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Analysis technology – leading-edge performance around the world

The Tascon GmbH company offers a comprehensive range of equipment for characterising surfaces and interfaces of nanostructured samples

DTascon GmbH is a company which offers analytical services and consultancy in the field of surface analysis. Tascon focuses on three techniques: ToF-SIMS, LEIS and XPS. The company additionally offers its customers other standard methods for surface analysis, including SEM. The company was set up in 1997 and its customers are to be found in a variety of areas and industries: semiconductor technology, automotive, coatings, glass, pharmaceuticals, medical technology and chemicals.

The company holds a flexible accreditation as a ToF-SIMS and XPS testing laboratory in accordance with DIN ISO/IEC 17025. This means that new analytical methods can be developed in-house and implemented directly. Tascon's success is based not only on the range of equipment it offers – always kept up to date – but also on its interdisciplinary team, recruited from the fields of physics, chemistry, biology, biochemistry and geology. The company has sites in Münster and the Rhine-Main area, as well as a subsidiary in the State of New York in the USA.

ToF-SIMS equipment for chemical surface analyses

How ToF-SIMS works

Briefly, in Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS), the surface to be analysed is bombarded with charged species (primary ions), which leads to the formation of a collision cascade in the sample. Part of the transported energy is directed back towards the surface where it leads to the desorption of atoms and molecules characteristic of the surface composition. Mass analysis of the charged species in a ToF analyser allows the identification of the surface components.

ToF-SIMS offers a high sensitivity (ppm/fmol), a high surface sensitivity (uppermost 1–3 monolayers) and is an imaging technique (lateral resolution < 100nm). Deeper layers can be accessed by sputtering, even for organic samples. Tascon is currently Europe's leading provider of analytical services using ToF-SIMS. In Münster it operates the world's largest commercial ToF-SIMS analytical laboratory.

LEIS scatters ions

In LEIS (Low-Energy Ion Scattering), the sample is also bombarded with ions. In contrast to SIMS, the energy of the scattered ion is used to determine the elemental surface composition. Noble gases are used as ions, and are directed at the sample at an energy level of some keV. Due to the nature of the scattering process, information is gained on the composition of the topmost outer layer as well as on the thickness and composition of underlying layers (down to some 10 nm)

LEIS is currently the most surface-sensitive process for surfaces and permits a standard-free quantification. Tascon is currently the only company in the world commercially offering analytical services with this technology.

XPS (X-ray Photoelectron Spectroscopy) offers information on the elemental composition down to

The team at Tascon GmbH led by Dr. Birgit Hagenhoff (4th from left)

some 10 nm and thus nicely couples into the LEIS and SIMS information. Additionally, information is gained on binding states and organic groups. This is achieved by exciting the surface with X-rays and analysing the energy of electrons freed in the photoelectric effect.

XPS provides quantitative information and supplies images with a lateral resolution of approximately ten micrometres.

The combination of the three techniques can be used in a variety of ways and with a high level of relevance to practical uses. The applications on surfaces and interfaces range from questions concerning the efficiency of cleaning processes to the field of reverse engineering.

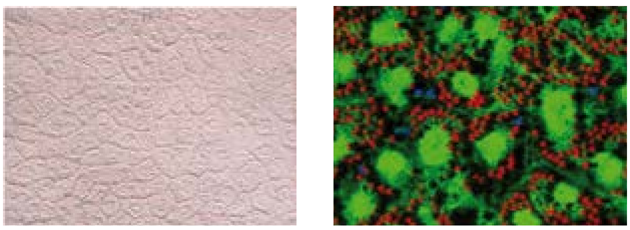

Image of microparticles of silicon oxide (diameter: two micrometres) in cells. Left: light microscopic picture; right: chemical lateral distribution at cell-core level (ToF-SIMS image). Key: red (silicon oxide), green (amino-acids in the cell nucleus), blue (substrate)

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Self-organization and equilibrium

In natural processes, structures and textures of the material create themselves

Aristotle's realization that the whole is greater than the sum of its parts is a guiding force today in studies on self-organization, self-assembly, and structure and texture formation on many length and time scales. The team led by Prof. Dr. Uwe Thiele is looking into how systems of soft materials organize themselves – on the way towards equilibrium and being permanently outside of equilibrium.

The spectrum ranges from the dynamics of cell aggregates, pattern formation in thin films of simple and complex liquids, and the dynamics of colloidal crystallization processes to data analysis and the control of complex systems. All these systems have one common feature: because of the nonlinear interactions of their subsystems, temporal, spatial and temporal-spatial structures develop which do not occur in isolated subsystems. The structures develop spontaneously through processes of self-organization and self-assembly.

Universal properties

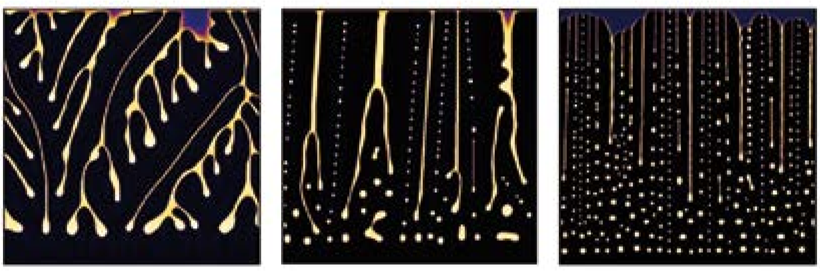
These processes have universal properties, which means that different types of system can be described by uniform mathematical concepts. Some examples of such structure formation are cloud patterns in the atmosphere, the formation of patterns in chemical reactions and self-organization in biological systems. It is in microphysics and nanophysics, in particular, that the concept of self-organization processes is growing in importance.

As it is becoming increasingly difficult on small scales to imprint structures and functions from the outside, one alternative worth pursuing is to use intrinsic self-organization mechanisms to induce and control structure formation. This is the aim that the team of researchers has. For example, they are analysing how colloidal suspensions of nanoparticles retreat from a solid substrate or crystallize. What is especially interesting here is how phase transitions (phase separation, evaporation, crystallization) interact with transport processes. The findings could be used to develop new processes for producing structured coatings.

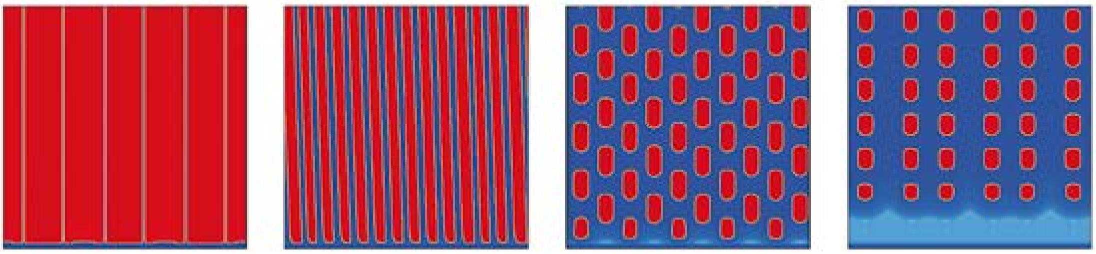
Layers from a molecule

Another focus of the team's work is self-organized structure formation in the coating of materials with so-called monolayers. These are layers which have a thickness of only one molecule. Theoreticians working in the team are developing dynamic models of the coating process in order to control this non-equilibrium process.

This is of fundamental interest because behind this is the question of how the combination of interactions on the nanoscale and controlled non-equilibrium processes produces order on the mesoscale. In order to be able to make statements on such systems and carry out detailed research into



Density profiles of nanoparticles, resulting as deposits from an evaporating colloidal suspension



Structure formation in simulations of the so-called Langmuir-Blodgett transfer coating process

the universal properties of non-equilibrium systems, the researchers use a variety of theoretical and numerical methods in their work. For example, they use methods from bifurcation theory, nonlinear dynamics and statistical physics – the theory of soft material and the theory of stochastic processes. The structure-forming processes are simulated and visualized on high-performance computers.

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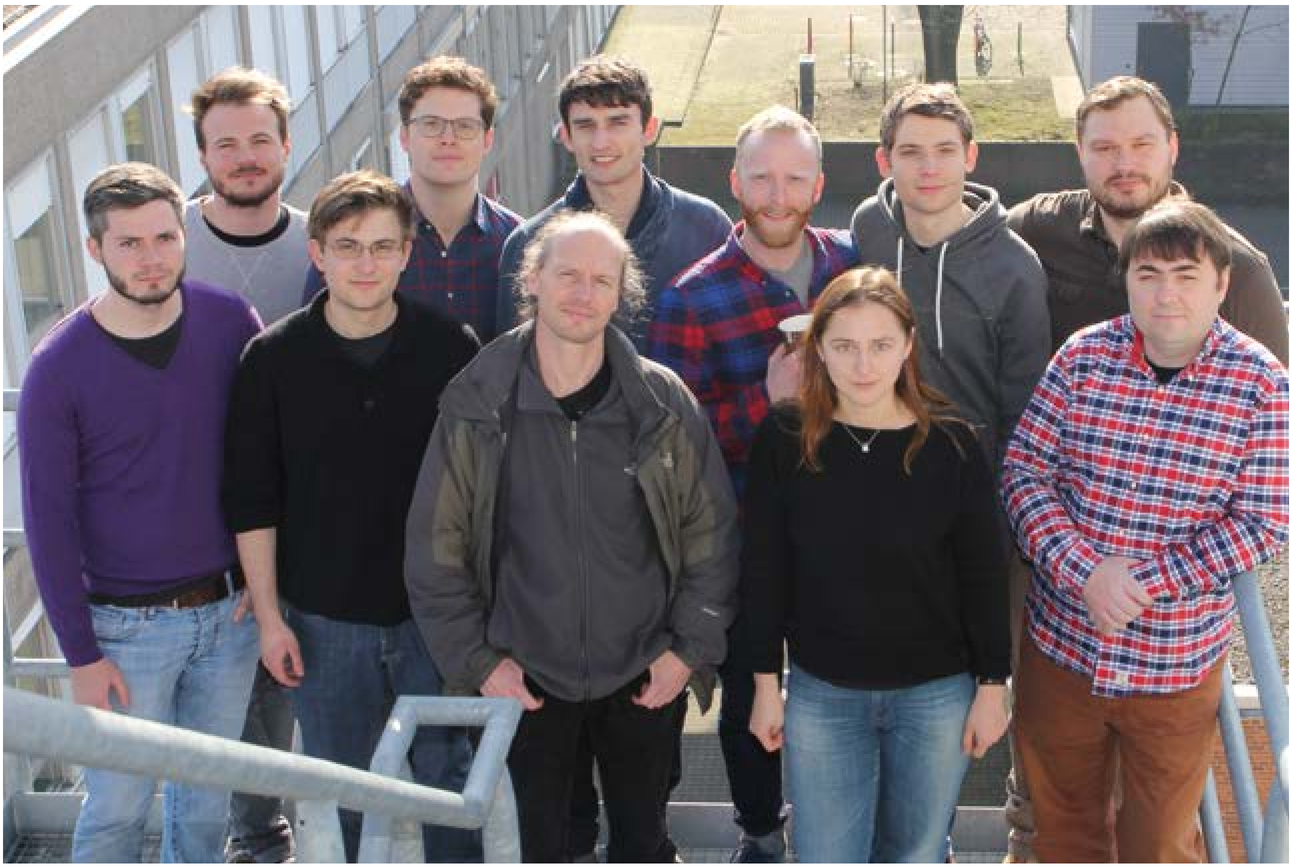
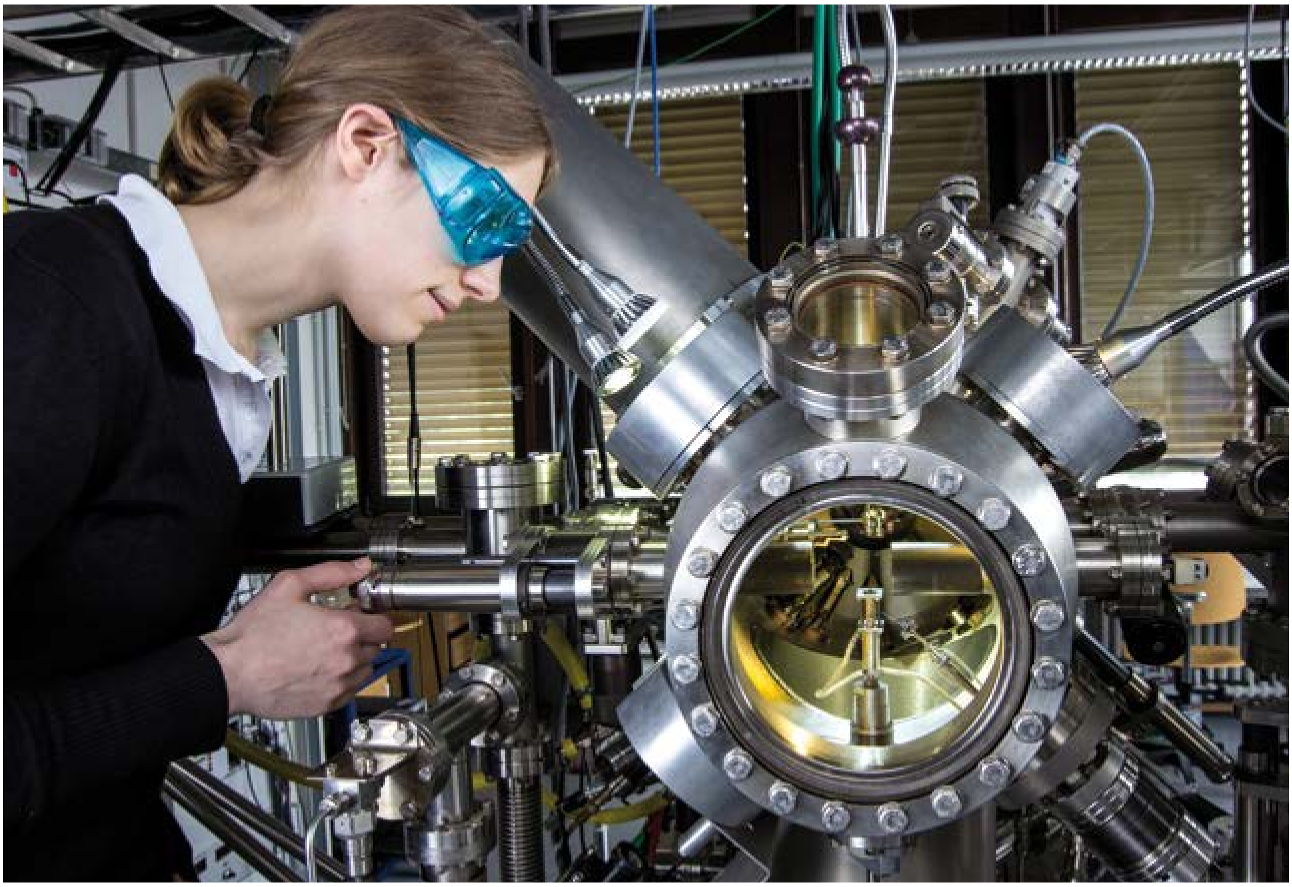


The team led by Prof. Dr. Uwe Thiele

With spin toward efficient electronics



Using state-of-the-art technology, researchers can penetrate deep inside the material's innermost secrets

Researchers are exploring the secrets of spin phenomena for novel electronic components

Spin is the intrinsic angular momentum of the electron. Among other things, it is responsible for magnetism. Magnetic phenomena currently play a major role in many areas of information technology. Magnetic layers serve as media for data storage. Magnetic read heads are found in hard disk drives of conventional computers and laptops. If electronic components are to become more energy-saving, and at the same time the data density and data processing speed are to be increased, there is no way around nanophysics.

For particularly efficient electronics, the aim is to use not only the electrical charge of electrons but also their spin as information carrier. This new type of information processing is called spin electronics, or spintronics for short. Prof. Dr. Markus Donath and his team are considered to be specialists in the use of sophisticated spectroscopic techniques for analysing the spin of electrons. The team is on the track of phenomena which can help to exploit the microscopic properties of spin on the macroscopic scale. As a result, this opens up ways of developing new applications in data processing.

A sandwich with extremely thin layers

The researchers want to understand, for example, how sandwich-type structures with extremely thin layers couple magnetically. Such magnetic sandwiches are used in the read heads of hard disk drives. For this purpose, the researchers dip into the microscopic structure of these layers. What is shown is that certain electrons feel that they are trapped in a sandwich when the layers are thin enough. It is precisely these electrons that give rise to the magnetic coupling.

The electron spin can also play an important part in non-magnetic materials. The current focus of interest is on surface alloys in which heavy elements such as bismuth, thallium or lead are embedded in the topmost atomic layer of metals such as copper or gold, or semiconductors such as silicon or germanium. In these cases, the electrons feel that there is a solid on one side and a vacuum on the other. This can result in the alignment of the electron spin, linked directly with the direction of the electric current. Such a property is promising for applications in the field of spintronics.

Preparing the electron spin

Experiments with spin-aligned electrons allow direct insight into the spin-dependent microscopic properties of magnetic and non-magnetic systems. Either spin-aligned electrons are used as projectiles or the spin direction is detected of the electrons which are emitted from the material sample with the aid of light. Both types of experiment are very elaborate and are therefore carried out by only a few teams worldwide.

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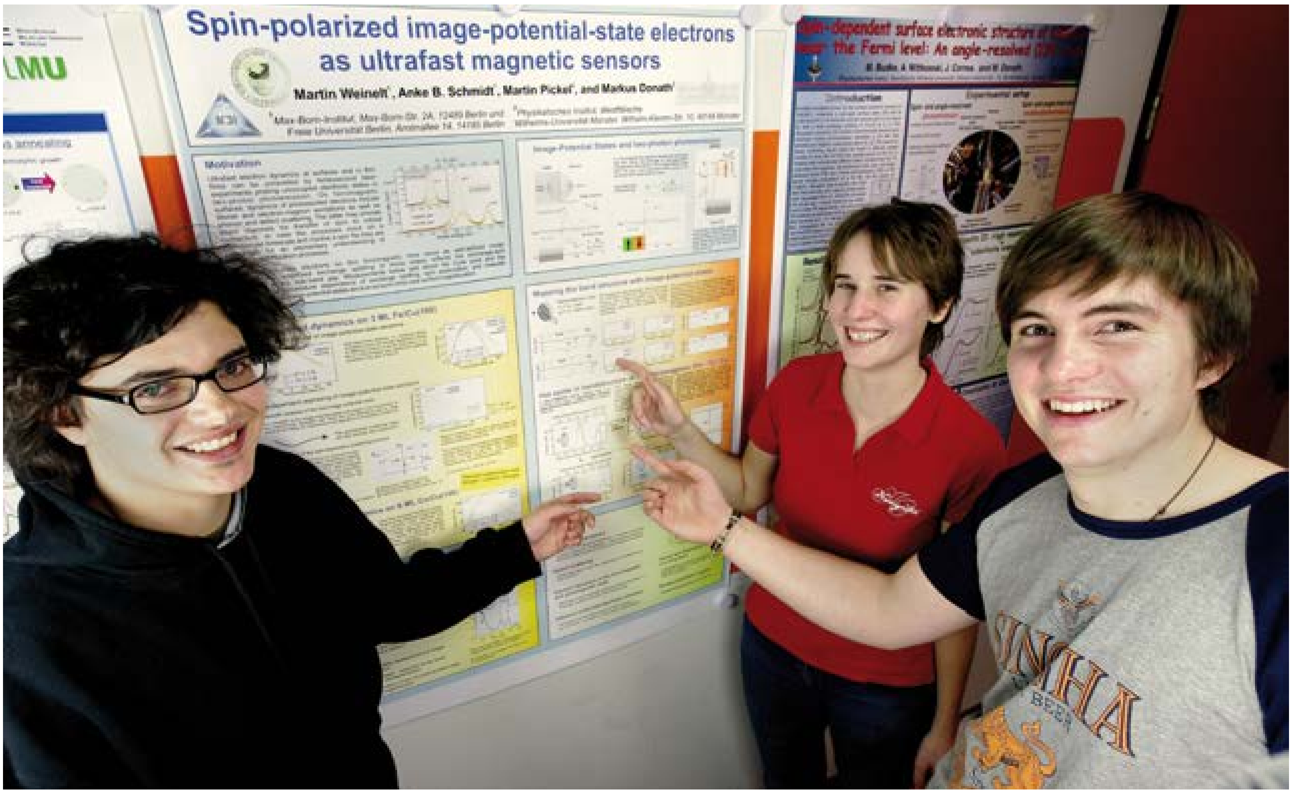
The team's analytical methods are extended by scientific techniques which investigate the precise chemical composition of the samples. The researchers are also able to clarify precisely the crystallographic order and the magnetic properties. In their research and experiments, Prof. Dr. Donath's team work closely together with other research groups at home and abroad, for example with the University of Halle-Wittenberg and the University of Hiroshima in Japan. Funding for the wide-ranging work is provided by the German Research Foundation, among others.



When the atoms in the computer are the model

Researchers under the leadership of Andreas Heuer simulate how complex processes run and how fine nanostructures are formed

Carrying out physics experiments is not enough to penetrate into the world of atoms and molecules and understand the microscopic interrelations. Thanks to modern computers and simulation techniques, it is possible to mathematically model and simulate the processes. To this end, Prof. Dr. Andreas Heuer's team of researchers use molecular dynamics and the so-called Monte Carlo method to find the answers to a variety of questions. The Monte Carlo method combines insights from statistical physics with principles of randomness.

Understanding the interactions

The basis for the simulations is an exact understanding of the interactions between molecules and atoms. Their movements can be described using mathematical equations which are solved with the aid of computers.

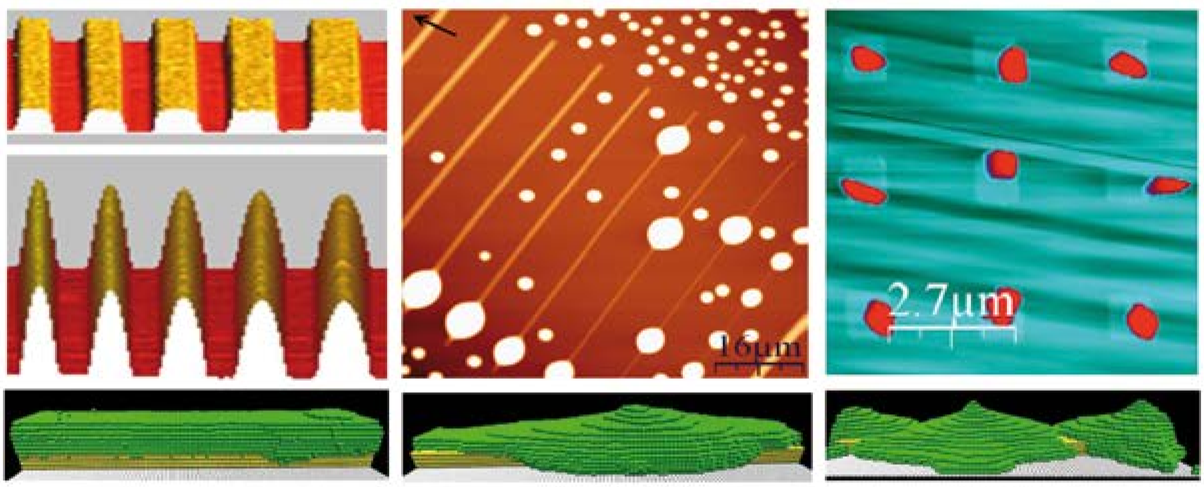
In the computer model, parameters such as the pressure or temperature of the relevant physical system can be varied. The model shows how the system's properties change. In the process, the researchers use simple or very detailed model systems, depending on the task in hand. One example is the control of nucleation on pre-structured surfaces. Teams of researchers led by Prof. Dr. Chi and Prof. Dr. Fuchs work together to try and separate out organic molecules with structures as regular as possible on pre-patterned surfaces.

An important step towards OLEDs

The structure of the surface often determines the resulting nanostructure of the molecules. If this is successful, an important step will be taken towards organic light-emitting diodes (OLEDs). To this end, molecular beam experiments are carried out. In the simulation, research is done into whether any additional – and thus disruptive – clusters are formed outside the pre-structured areas.

This process is described with a certain probability, the common name for it being nucleation. For other pre-structured geometries, the aim is to analyse whether highly ordered clusters can occur. Suitable model systems permit such processes to be analysed with a combination of the Monte Carlo method and analytical studies.

In a Chinese-German research project (TRR 61), there is close coordination between the theoretical work and the physics experiments carried out. For example, investigations are undertaken into what



The resulting arrangement of molecules separated out on a pre-structured surface. Top: experiments for various molecules. Bottom: simulations for various strengths of interaction between the molecules.

influence the geometry of the pre-structured patterns or the properties of the molecules have on nucleation. Other exciting questions concern the instabilities of coverage phenomena, which can be observed both experimentally and in simulations.

Simulations of complex systems

One central concept in physical research into nanoscopic systems is that of energy. Energy is behind all processes, whether they be complex biological molecules or atomic clusters. The researchers have developed various methods for describing the dependence of energy on the concrete structure, as well as for identifying the coordinates with which the dynamics of the complex system can be captured in the best possible way.

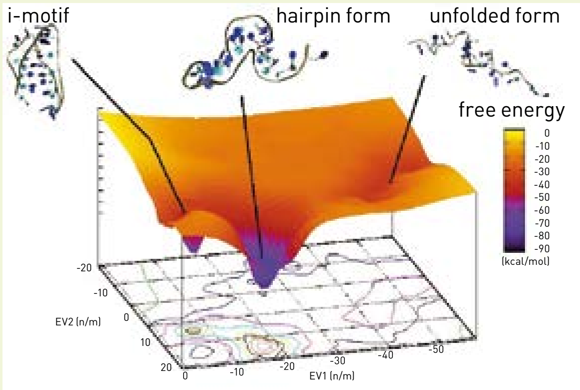
The challenge is then to characterize the so-called free-energy landscapes of the complex system by means of computer simulations. For this purpose, suitable algorithms are needed such as those being developed by Prof. Heuer's team of researchers. For some glass-forming systems it is actually possible to numerically determine properties of the potential energy landscape.

Afterwards, the findings related to the nature of the energy landscape have to be translated into physically observable magnitudes. This can be a reaction rate, for example. Only then can the results of the simulation be compared with the measurements from the physical experiments.

How does DNA unfold?

Together with experimental groups from Beijing, the Münster researchers are investigating in their simulations how individual molecular forms of DNA such as the i-motif can fold and unfold. The i-motif consists of single-strand DNA which arranges itself in such a way that the result is a kind of box-shaped object.

By means of simulations, the free-energy landscape in the unfolding and folding of the i-motif can be determined (here, at 400 kelvins). The troughs show individual stable forms, which are represented graphically. The folding pathways are connections between these troughs. The i-motif unfolds via a hair-pin structure as a very stable intermediate state before becoming a stretched form. Technologically, this structure can be used above all with nanoarrays. A large number of these strands are arranged on a carrier, and the reversible folding and unfolding can be used to carry out work.



Equally, nanocontainers can be fabricated from these structures, which make targeted unfolding possible – for example, to release substances fixed in the DNA matrix, as the researchers in Beijing have already impressively showed. Finally, hybrid systems of DNA strands and polymers are also being studied, and a broad range of self-organizing mechanisms can be observed. The computer simulations are an aid to understanding the underlying mechanisms.

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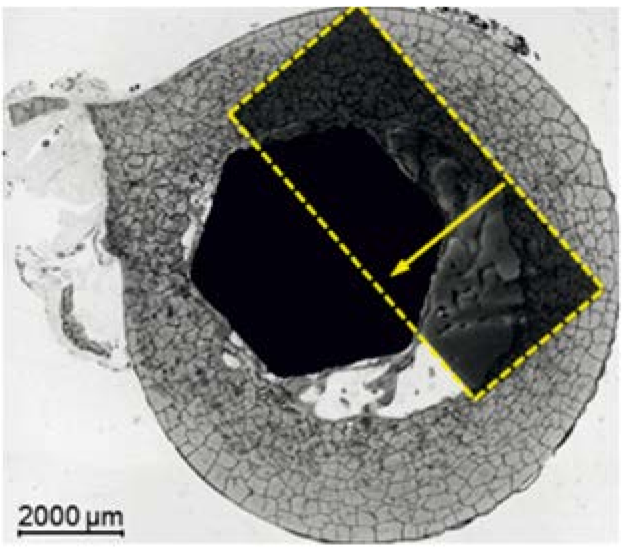
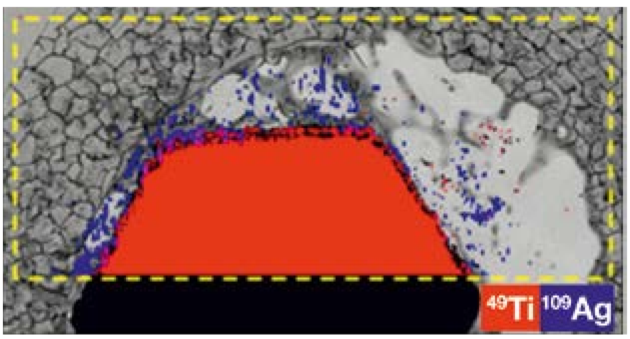
An image is worth a thousand words

In order to investigate the distribution of elements in tissues, the team of researchers led by Uwe Karst ablate their samples with a laser. Through a connection to plasma mass spectrometry they get a completely new view of things

Over the past few years, modern analytical chemistry has developed a large number of methods – especially in the field of hyphenated techniques – which deliver valuable insights for finding answers to biological or medical questions. These hyphenated techniques are characterized by the fact that two originally independent analytical methods are combined in an appropriate way to obtain more information on a sample. The questions that have to be answered often arise from the use of nanoscale systems such as special surface coatings or nanoparticles, which – advertently or inadvertently – come into contact with tissues.





Top: Metal implant in a bone. The area examined using LA-ICP-MS is marked yellow. The arrow shows the direction of the laser scan. Below: superimposed elemental distributions of titanium and silver in the ablated area

From the laser shot to the image

Coupling a laser ablation system (LA) with inductively coupled plasma mass spectrometry (ICP-MS) – as is used in Prof. Dr. Uwe Karst's team working at the Institute of Inorganic and Analytical Chemistry – allows to determine many elements, particularly metals, in sections of tissue at trace and ultra-trace concentration levels. Laser ablation ICP-MS is characterized by very good detection limits in comparison with many X-ray spectroscopic methods. In the process used here – usually abbreviated to LA-ICP-MS – the sample is ablated linewise by a laser beam in an ablation chamber. Typical instruments allow using laser spot diameters between four and 200 micrometres.

As a result of the laser irradiation, the sample material is removed (ablated), transferred into the gas phase and transported by a flow of argon gas or helium gas into the inductively coupled plasma, where there are temperatures of several thousand degrees centigrade. After atomization and ionization, the elemental ions (e.g. silver ions or titanium ions) are transferred to the mass spectrometer, where, on the basis of their characteristic ratio of mass to charge, they are separated and detected.

Silver migrates into the tissue

As a result, this provides the relevant qualitative and quantitative information on the elements for every ablated spot. The sample is scanned linewise. After the signal is converted using appropriate software, an image is provided of the distribution of elements in the tissue section. This is known as elemental bio-imaging.

Working together with the Department of Experimental Orthopaedics at Münster University Hospital (Dr. Gregor Hausschild and Dr. Steffen Höll), and using LA-ICP-MS, the osseointegration (ingrowth behaviour) of metallic implants based on titanium in hard and soft bone tissue was examined.

The implants were coated with nanoparticulate silver, which is designed to reduce the infection rate due to its bactericidal effect. The image on p. 80 (bottom left) shows how the elements titanium (Ti, red) and silver (Ag, blue) are distributed in the surrounding bone tissue. In this way, it was possible to detect silver up to a distance of 750 micrometres from the surface of the implant.

These investigations allow assessing how silver behaves in tissue and whether any further distribution of the silver within the organism can be expected. To quantify the silver, matrix-matched standards are prepared and used for external calibration.

Absorption through the airways

(Nano)particulate silver may not only enter the organism by coated implants, but also through inhalation, i.e. absorption through the airways. One example is the use of silver in body-care products such as deodorant sprays. As the organism treats such particles as foreign bodies, it is important to find out in which form they exist in lung tissue after being inhaled. For this purpose, Karst's team developed a method based on LA-ICP-MS, which permits a quantitative and spatially resolved detection of single particles in tissues. With the aid of this so-called SP-LA-ICP-MS (SP = single particle), single nanoparticles can be determined in solid samples with good detection limits. Conclusions can also be drawn relating to the size distribution of the particles.

In elemental imaging, analytical chemists have, in the LA-ICP-MS, a high-performance tool which helps to provide answers to many questions. In the future, the challenge will be to link the results from this method with other imaging processes and to improve the resolution in the systems.

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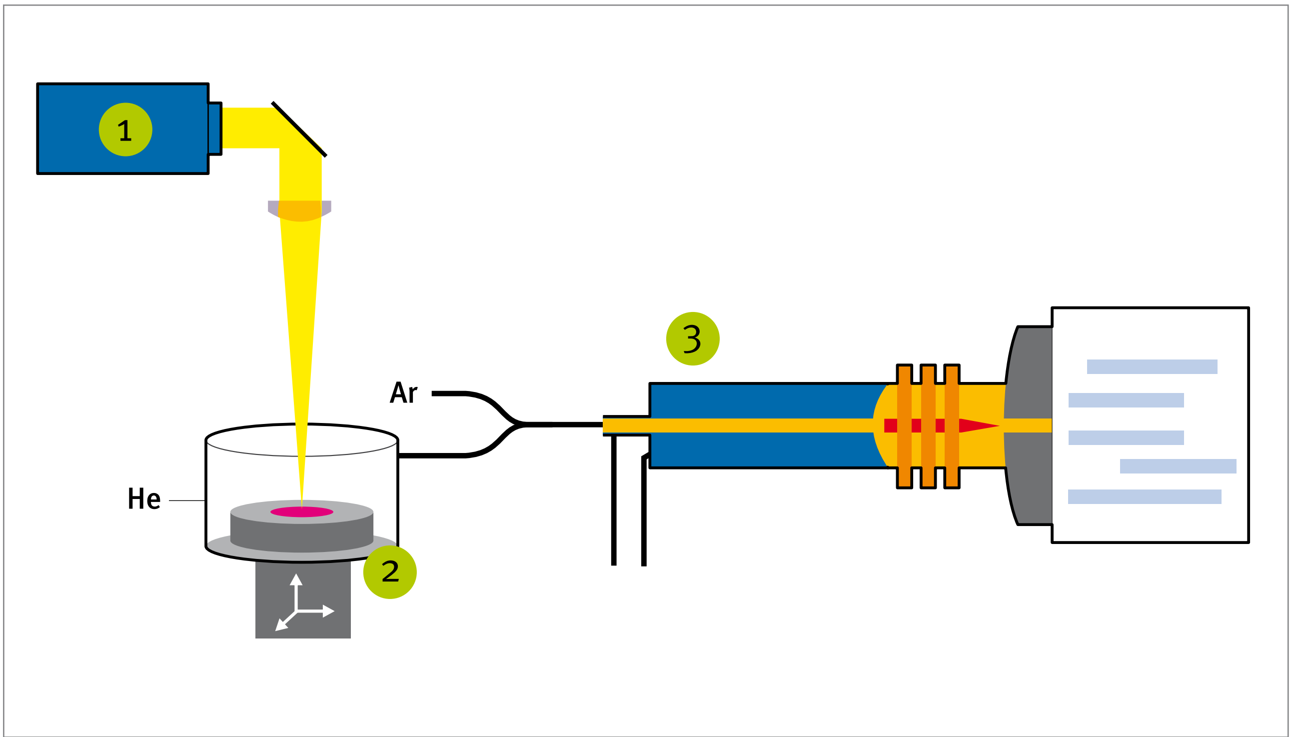
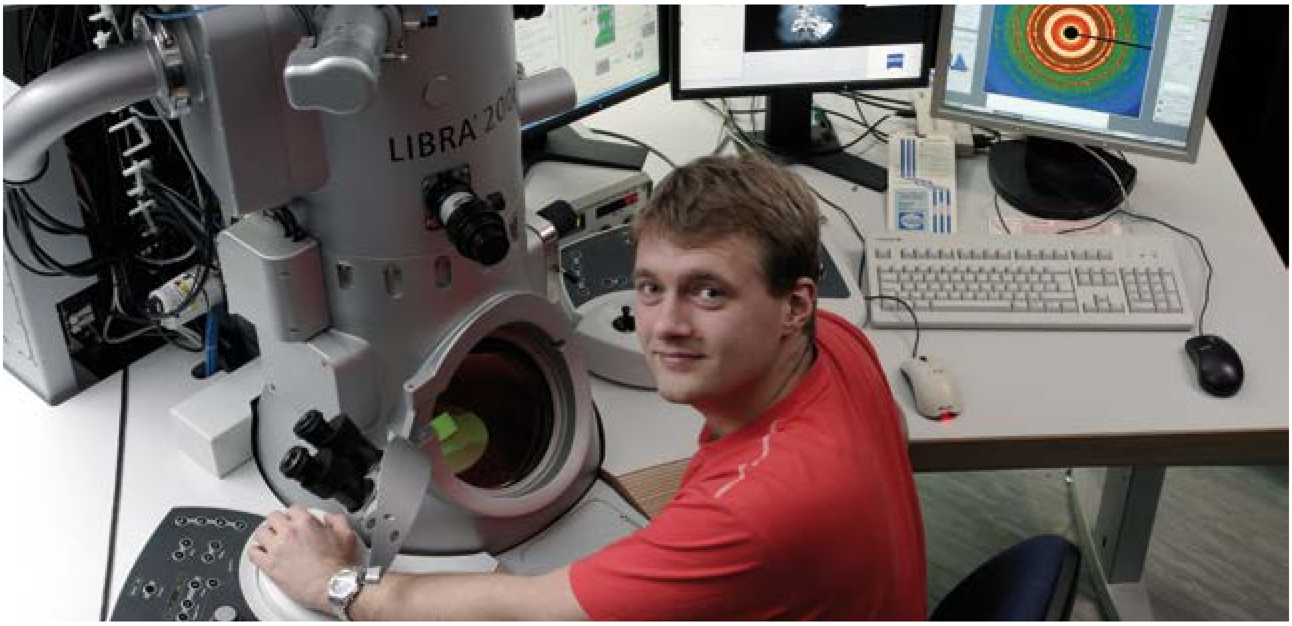


1 laser, 2 ablation cell, 3 ICP-MS

To one five-millionth of a millimetre exactly



One of the researchers in Prof. Dr. Helmut Kohl's team examines a sample through the electron microscope

Researchers need special electron microscopes to discover the secrets of atoms and molecules

Researchers have a lot of technical equipment and analytical methods, which they can use for new findings from the nanocosmos. These include scanning probe microscopes, which can elucidate the surface of a sample precisely to millionths of a millimetre. In contrast to this technology, transmission electron microscopy also makes it possible to investigate the entire volume of a thin sample.

The "Quantitative Electron Microscopy" team led by Prof. Dr. Helmut Kohl uses transmission electron microscopy in order to make atoms visible at distances of one five-millionth of a millimetre. That is two-tenths of one nanometre – approximately the diameter of a single atom. Such microscopy is able to depict the atomic structure of crystals.

With this kind of electron microscopy, different sorts of atoms (elements) cannot be distinguished. A trick is used to determine an element precisely. The electrons initially all hit the sample with the same energy. As they cross the sample, however, they lose differing amounts of energy. This loss and, as a result, the remaining energy depend on the chemical composition of the sample. By means of an energy filter, it is possible to get only electrons with a pre-selected specific energy loss to be part of the image. This means that the distribution of the individual elements becomes visible. The brightness of the image grows in proportion to the local number of atoms in the elements being sought.

The aim of the research being done is to improve the methods used to make quantitative assessments of the digitally recorded images and to improve the detection limits in chemical analysis. In the samples, the chemical composition was determined with a resolution of approximately one nanometre.

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Nanophysics in the virtual laboratory

The periodic table as a building kit: computer simulations help in understanding experimental findings and provide new impulses

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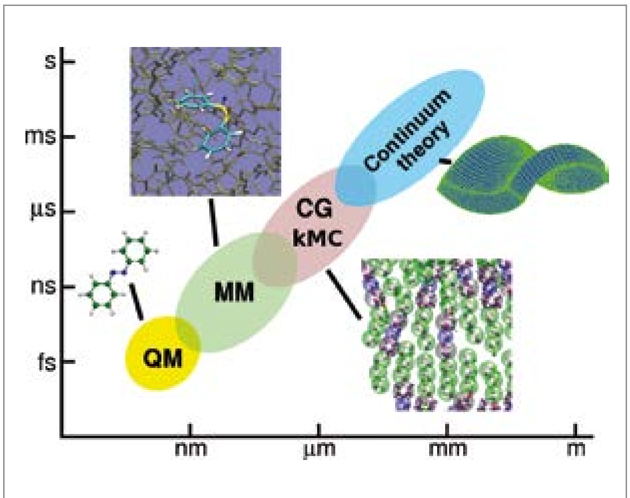
The basic physical equation describing the motion of atomic nuclei and electrons in molecules and condensed matter has been known since the beginnings of quantum mechanics almost a hundred years ago. Today it can be solved for systems relevant to nanophysics with a good degree of accuracy by using high-performance computers and modern computer algorithms. In this way, physical properties can be predicted in the "virtual laboratory" and new materials discovered.

Light-sensitive materials

One focus of the work being done by the team led by Prof. Dr. Nikos Doltsinis is the interaction between light and matter. There is a particular interest in materials, for example, whose properties can be switched by light. Another aim is to understand in detail how new types of organic solar cells function, in order to gain information useful for producing solar cells, which have improved efficiency. Because of their high computational demand, quantum mechanical simulations for processes with large numbers of particles, or which need longer periods of time, come up against the limits of what is feasible. Typically, the model dimensions lie in the nanometre range and the simulated time windows on the picosecond scale.



Typical length and time scales in different theoretical methods: quantum mechanics (QM), molecular mechanics (MM), coarse-grained (CG), kinetic Monte Carlo (kMC) and continuum theory

Hierarchies of models

One of the greatest challenges facing researchers is in developing so-called multi-scale methods, which can be used to bridge several time and length scales as far as realistic macroscopic phenomena. For this purpose, the Doltsinis team is developing hierarchies, which build on one another, of simplified classical models whose common origin lies in quantum mechanical reference calculations. These are currently applied, for example, in the simulation of liquid crystals and organic semi-conductors.

From wind turbines to nappies

OFG Analytik GmbH is a company which can look back on 25 years of experience in the analysis of nanotechnology products

The modern world can scarcely be imagined without nanotechnology. If nanoscaled additives for varnishes are to be characterized, or extremely fine structures made visible, or functional coatings chemically analysed, then complex methods and equipment are needed for the task. OFG Analytik is a private company in Münster and began offering such high-level services to industry in 1993, thus enabling business to make use of this advanced technology. Set up by two developers of the TOF-SIMS process plus one chemist, the company can draw on more than 25 years of experience in the development and use of nanoanalytical processes and in the optimization of industrial production processes.

Special nanocoatings improve the properties of industrial products in a variety of ways. Nowadays, their uses stretch to almost all areas of technology and everyday consumer goods. Nanomaterials improve the scratch resistance of automotive coatings, increase the weather resistance of textiles or improve the surface properties of rotors.

Highly sensitive methods for certification

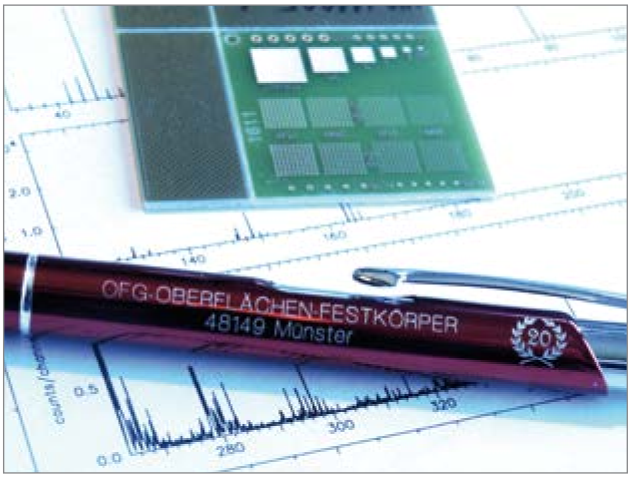
They are used in cosmetics as much as in coating systems. Chemically characterizing these materials and surfaces and, for example, finding out why a nanocoating has failed to function properly, is an important field of work for the experts at OFG-Analytik GmbH.

Nanoscale filler material and additives to coatings are increasingly being used not only in the automotive industry but also in exterior paints and wood coatings. Certification, chemical characterization and analyses of its distribution in multi-layer systems all require complex processes. OFG Analytik has the most advanced analytical methods for this work, such as TOF-SIMS and field emission, scanning electron and infrared microscopy. Special methods have also been developed in collaboration

Using highly sensitive analytical methods such as TOF-SIMS, OFG-Analytik supports industry in the fields of research, development and failure analysis

Metallic surface made hydrophobic through nanocoating with manufacturers all over the world. These enable the company to carry out analyses using state-of-the-art technology. This means that questions such as the following can be answered:

- How do discolorations in rain gutters occur?
- Why does a coating's adhesion not function properly?
- Why do printing flaws occur on bottles of shampoo?
- When do agglomerates form in nanoscaled pigments?



Wide variety of applications

Researching and using nanocoatings opens up a wide variety of applications, for example in increasing the efficiency of solar cells and wind turbines, or in protecting against corrosion for cladding panels, or in improving the scratch resistance of coatings. This potential has still not been exhausted. Therefore, in the development of innovative coating processes and to find out more about interface phenomena, not only industry but also universities and research institutes of the Fraunhofer Gesellschaft are only too pleased to draw on OFG Analytik's tailor-made concepts when investigating problems.

In addition to laboratory analyses, the services offered by OFG Analytik include professional sampling, advice either on the spot or by telephone, research work and seminars. A comprehensive knowledge database – the result of more than 20 years of business experience in surface and materials analytics – is available for dealing with highly complex questions both fast and competently. This ranges from express analyses in the case of halts to production to development projects stretching over several months.

The properties of coatings surfaces are set as required through the use of nanoadditives

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Analytics: anything but superficial

nanoAnalytics is a company using modern analytical equipment to deal with questions relating to surface technology and life science

Surfaces and interfaces play an important part not only in many technical processes and products, but also in biological systems. nanoAnalytics is one of the leading providers of analytics services and special measuring equipment in this field of research and failure analysis.

The macroscopic properties of materials are often clearly influenced by structures at the microscopic or even molecular level. Modern analytical methods are of considerable importance in quality assurance or research.

This is true not only for analyses of the chemical composition of surfaces, but also for a precise measurement of surface topographies. In some cases, the measuring equipment has to record and depict structures down to nanometre level.

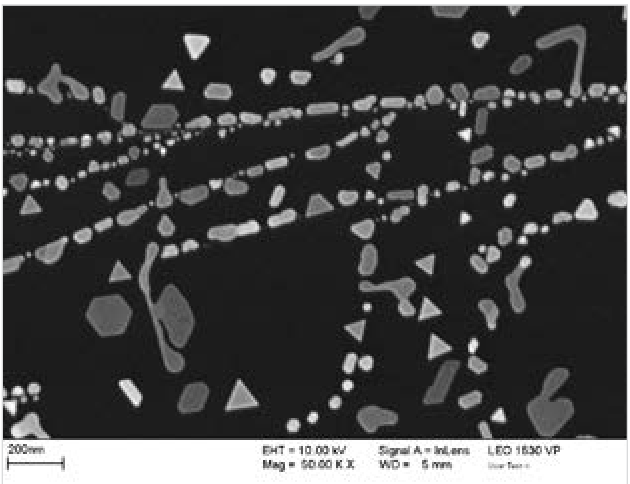
An eagle eye for quality

In the industrial production of special surfaces, mechanical or chemical pre-treatments or coatings are often decisive for the usage properties of a product, as well as for its service life. Surfaces are cleaned or activated in order to remove impurities or to ensure a defined morphology. In order to monitor such processes, nanoAnalytics use a large number of very sensitive modern analytical methods. For example, the surface of a workpiece, after it has been degreased, can be very thoroughly examined for remnants of grease or cleaning materials. Such remnants are problematic if, for example, an adhesive bonding subsequently has to be produced.

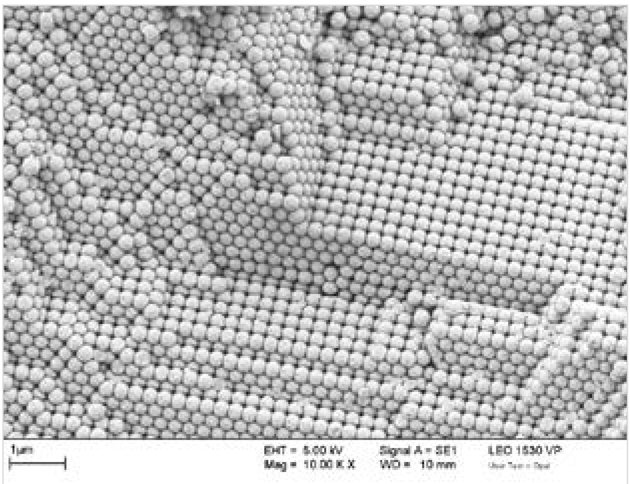
Looking for faults

The analyses undertaken by nanoAnalytics help in looking for faults in the pre-treatment or in the optimization of process parameters such as the cleaning time needed for baths, or their service life. However, the right measuring equipment is not always available in every company. If necessary, a professional and independent laboratory is often used which offers the required analytical method and construes the data to answer the questions in a fast and competent manner.

nanoAnalytics is an independent, accredited testing laboratory and is specialized in such analyses. It offers companies and research institutes a broad range of services in the field of analyses of surfaces and interfaces.



High-resolution electron microscopy image of antimony on graphite



Depiction of an opal using a scanning electron microscope (SEM)

New lab equipment: cellZscope

Experimental analyses of biological cells often provide only snapshots. Typically, cells need to be fixed and stained with dyes, which is a massive intervention in biological processes. But cells are living things and they constantly change.

To understand biological processes in cells better, a measuring system is needed which ideally does not interfere with or change the cells, and which continuously provides data. Only then can the dynamics of the cellular processes be recorded, for example the reaction of cells to pharmaceuticals, growth factors or cytostatic drugs.

The cellZscope developed by nanoAnalytics in collaboration with the University of Münster is a new laboratory device for measuring the electrical properties of epithelial and endothelial cell layers under physiological conditions. The cells are cultivated on porous membranes of standard inserts.

Computer-controlled analysis

With the cellZscope cells under investigation can remain in the incubator all through the experiment. The simultaneous analysis of up to 24 cell cultures is computer-controlled, even over longer periods of time lasting several hours or days, without any manual intervention being necessary. The cellZscope allows the continuous and automatic analysis of the barrier function of interface tissue, in particular the influence of drugs, substances or particles.

This is of particular use for scientific studies on pharmaceutical resorption, cytotoxity or the formation of metastases in tumour cells. More information and examples of applications can be found on the nanoAnalytics website: www.nanoanalytics.de.

The cellZscope is a device for the characterization of barrier-forming cells. It is ideally suited to investigate the influence of drugs or toxins on the barrier function of epithelial or endothelial cells under physiological conditions

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A specialist lab for molecular biomedicine

arrows biomedical is a company offering a wide range of services in the fields of molecular oncology, human genetics and neuro-degenerative diseases

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arrows biomedical Deutschland GmbH was founded by Dr. Arnold M. Raem in 2005. Since then it has been located within the Center for Nanotechnology (CeNTech) at the University of Münster. The laboratory is currently in the process of being accredited (DAkkS) for the fields of molecular pathology, human genetics and biobanking for special demands in research and development and as a routine clinical laboratory. arrows biomedical carries out not only commissioned research, but also routine clinical analyses, as well as research and development projects of its own.

The portfolio of molecular analytics

The focus is on molecular research into cancer as well as on neuro-degenerative diseases. The portfolio of molecular analytics comprises services on analysing DNA / RNA and, derived from this, proteins (RNS), microarrays (GenExpression, mRNA miRNA, Array-CGH, ChIP on Chip), PCR (RT-qPCR) and bioinformatics. In the field of medical diagnostics, the routine analyses cover all clinically relevant bio-markers as well as the complete range of blood analyses, flow cytometry, HPLC analytics, diagnostic micro-arrays, verification of freely circulating tumour cells and chemosensitivity testing. The company has at its disposal not only all the relevant sequencing methods (Sanger, Pyro- and NGS), but also a wide range of microscopy technologies (including MetaSystems software). Cell-culture applications are also used in the company's laboratory.

Collaborations all over Europe

The company's cooperation partners in industry and at universities are to be found all over Europe. It receives commissions from public health institutes and registered doctors, state research insti-

tutes, the Max Planck Institute for Molecular Biomedicine in Münster, the German Army and the German Aerospace Centre. Projects in the field of Research and Development which arrows biomedical undertakes on its own are funded by the German Ministry of Economics and Technology and by the German Federation of Industrial Research Associations. The company has submitted applications for funding to the European Union, the German Ministry of Education and Research and the state of North Rhine-Westphalia, and these are at the approval stage. An application to the Institute for Remuneration Systems in Hospitals in Siegburg has already received a positive response. arrows biomedical combines state-of-the-art technology with complex data analyses to produce meaningful results in an easy-to-understand format. The company has also produced numerous scientific publications which have appeared in scientific journals and books. Its success is rooted in maximum customer satisfaction.

The company is a recognized centre providing further training for human genetics specialists. Also, it is a cooperation partner of the Institute of Pathology at Trinity College Dublin, in Ireland.

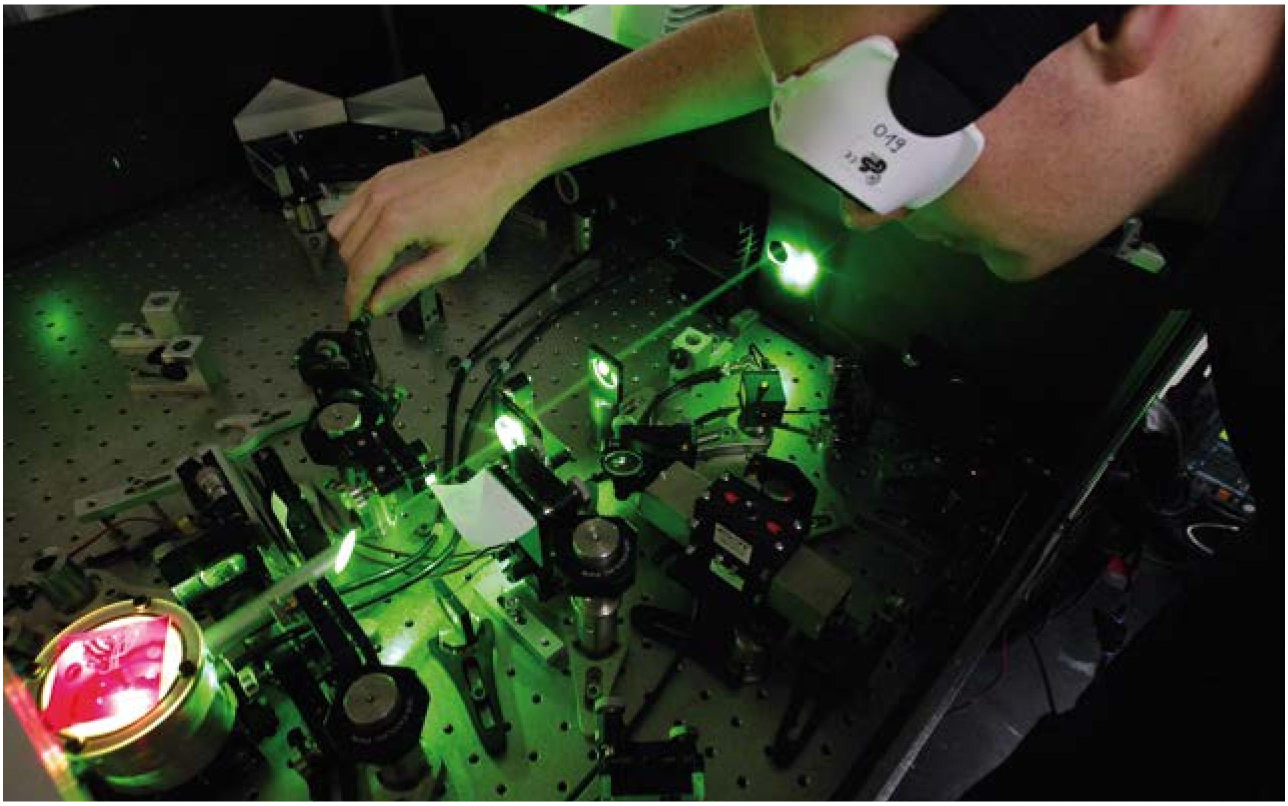
Ultrashort measurements with strong lasers

Extremely high energies and short pulses: in nanoanalytics, researchers are pushing back the boundaries of knowledge ever further

A central characteristic of nanostructures is that their properties are very different from those of volume materials. Besides changed optical properties, it is above all their interaction with their surroundings that is different. Their catalytic reactivity and efficiency is mostly increased, and new functionalities can be produced with suitable methods. The focus of the research group led by Prof. Dr. Helmut Zacharias is on developing processes which can be used to investigate the atomic and molecular movements of nanostructures.

As this movement takes place in an ultrashort timespan, laser processes are used in which individual laser pulses only last some tens of femtoseconds. Such lasers first have to be built, because equipment commercially available is not satisfactory when it comes to meeting the requirements. One example is the titanium-sapphire laser, which achieves a high pulse energy with a high repetition rate. This laser works in the red spectral range with a wavelength of 800 nanometres, a pulse duration of 35 femtoseconds and an unfocused intensity of 150 gigawatts. This is an unbelievable output – almost twice as high as all the power plants in German together, realized in an equally unbelievable time of 35 femtoseconds – 35 thousand billionths of a second.

In addition to the red frequency range, important information is also gained by using extreme ultraviolet radiation and X-rays. It is for this reason that, for some time now, one focus has been on generating radiation with an ultrashort pulse duration in this spectral range so important for nanoanalytics. As the wavelengths are very short, it is not yet possible to generate such frequencies directly from a compact laboratory laser.



Laser technology provides researchers with new tools for their experiments.

Therefore, a roundabout route has to be taken via the red titanium-sapphire laser. Using a variety of tricks and special interactions, radiation – which is laser-like, bundled and coherent – can be generated in extreme ultraviolet. The light pulses are extremely short – less than ten femtoseconds, and even down into the attoseconds range.

As a result, it is possible to analyse ultrafast electronic processes which play a major role in photosynthesis, for example, or in the vision process of the human eye. The researchers are treading new paths by investigating plasma processes which, it is hoped, will lead to higher intensities of the radiation generated. Investigating the dynamics of bound and unbound electrons requires light energies in extreme ultraviolet with wavelengths between ten and 100 nanometres.

Millions of gigawatts bundled

If the radiation output from the laser reaches millions of gigawatts per square centimetre, it is possible to generate such radiation – so-called high harmonic generation – in gaseous targets by using a frequency multiplication process. Up to now, noble gases were generally used for this. Metal vapours are particularly interesting, though, because in this case resonances can be used to achieve much higher intensities. The researchers in Prof. Dr. Zacharias' team use a laser pulse to vaporize metals from a fixed target.

In this metal vapour, a second laser pulse – synchronized and particularly intensive – then generates so-called high harmonics. This novel process has already resulted in intense radiation in extreme ultraviolet in carbon, aluminium, copper, silver, zinc, tin and indium. It has also been possible to generate such radiation in nanoparticles. In the case of tin and indium, increased yields could also be observed in the vicinity of resonances. One of the aims of current research is to gain a better understanding of these processes of generation and to optimize them so that the radiation generated can be used in investigations of the electronic dynamics of molecules and adsorbates. This includes using tricks to prevent the normal widening of the time gap between the generating pulse and the generated high harmonics.

Catalysis: the last step

It is often desirable to have a depiction of the nanosystem stimulated, with time resolution if possible. For this purpose, the researchers use so-called photo-emission electron microscopy (PEEM). Currently, photo-electrons from the valence bands are the focus of attention. This makes it possible to discover electronic properties of nanostructures with a lateral resolution of down to ten nanometres.

Finally, using time-correlated double pulses, the researchers analyse the dynamics of molecular desorption in specially prepared layer systems, currently graphite, graphene and graphene nanoribbons with a width of only 0.74 nanometres. In this way, their aim is to learn something about the electron transfer processes which lead to reaction and eventually the desorption of adsorbed molecules. Desorption is the last step common to all catalytic surface reactions: the photocatalytic splitting of water to produce hydrogen, in the catalytic converter of a motor vehicle or in large-scale chemical processes such as ammonia synthesis.

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Ultrafast quantum dynamics in nanostructures

Ever smaller semiconductor structures and faster switching processes mean new components for information processing

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Because of technological progress, electronic components such as processors or storage elements in computers are becoming ever smaller and, at the same time, ever faster. Typical dimensions are already in the range of just a few nanometres today, which means a length scale at which the atomic structure of the material plays an increasingly important role. Times are also getting into the range of typical elementary interaction processes through which, for example, energy can be exchanged between the electrons and their surroundings.

Both of these mean that the dynamics of such systems are increasingly deviating from traditional behaviour and, instead, are being determined ever more strongly by the laws of quantum mechanics. While this is extremely detrimental for very modern computers, using quantum effects opens up entirely new possibilities such as secure encryption techniques as part of quantum cryptography, or information processing on the basis of single atoms or atom-like systems in a quantum computer. As the laws of quantum mechanics are often very abstract and difficult, a detailed theoretical modelling is indispensable for understanding. In the team led by Prof. Dr. Kuhn, such theoretical analyses of ultrafast quantum dynamics are carried out for nanostructured solid-state systems.

Artificial atoms

If, in a semiconductor, the motion of the electrons in all three spatial directions is restricted to just a few nanometres, a so-called semiconductor quantum dot is formed. Here, similarly to atoms, a quantization of the energy states occurs, i.e. the energy of the electrons can no longer assume arbitrary values, but only very specific ones. This is why quantum dots are also known as artificial atoms. In contrast to real atoms, however, their possible energy values can be controlled to a large extent through geometry and the composition of the material.

Such structures are therefore very interesting both for optical devices such as semiconductor lasers and for applications in quantum information technology. One thing the team is investigating is how such quantum dots interact with their surroundings.

The optical excitation of a quantum dot with an ultrashort light pulse results in a certain part of the energy input being radiated very fast on a time-scale below one picosecond (a millionth of a millionth of a second) in the form of lattice vibrations, i.e. a soundwave. The remainder, by contrast, is emitted in the form of light on a time-scale one thousand times longer. Interestingly, the quantum state of the lattice vibrations thus generated can to a large extent be influenced by optical stimulation.

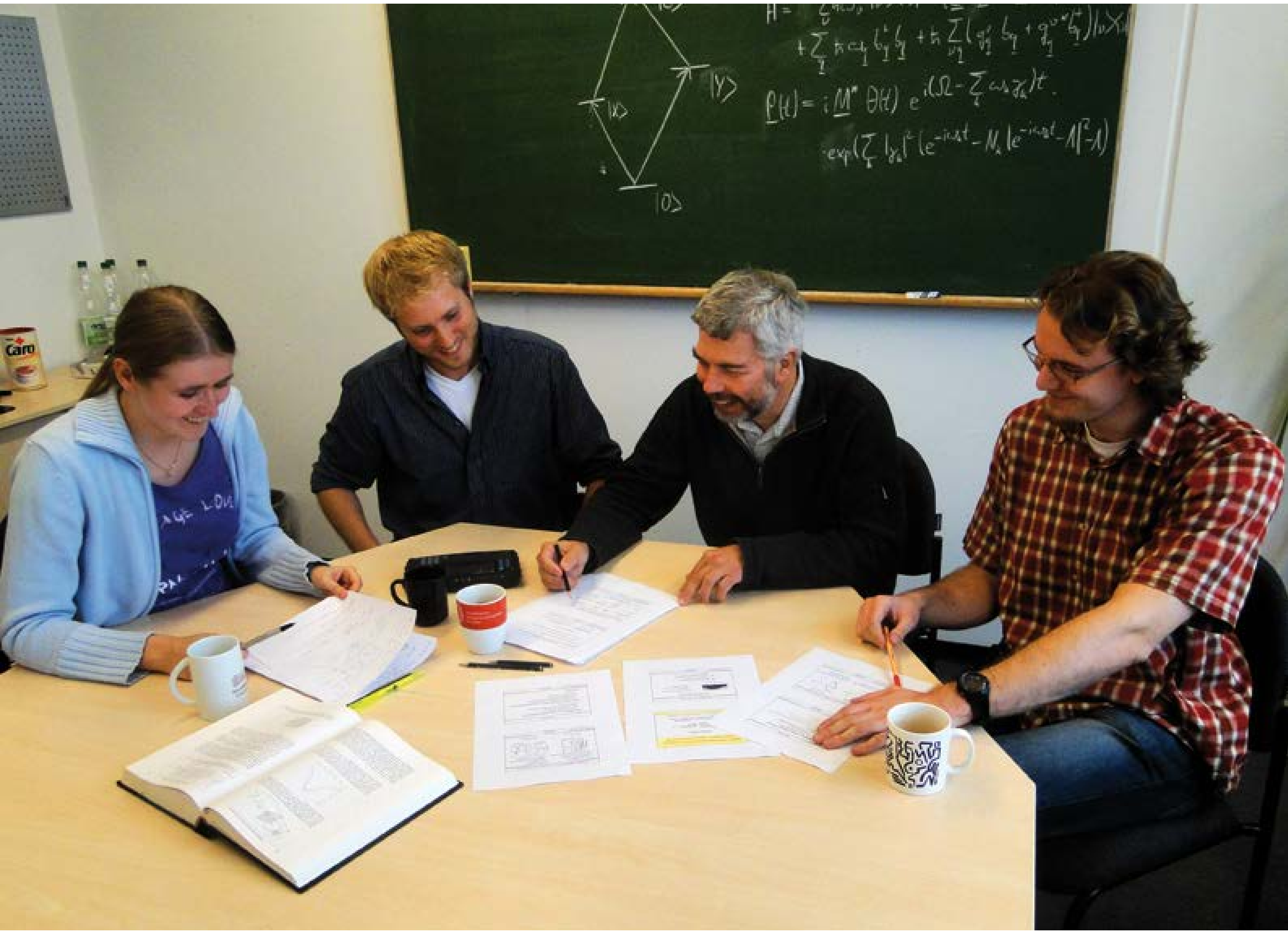
An excitation with two ultrashort light pulses, for example, can generate non-classical states in which the fluctuations are temporarily smaller than in a quantum vacuum. Such so-called squeezed states are well known in quantum optics for the light field. Besides being genuine quantum states and hence of fundamental interest, they play a major role in measurements for which extreme sensitivity is required.

The spin of a manganese atom

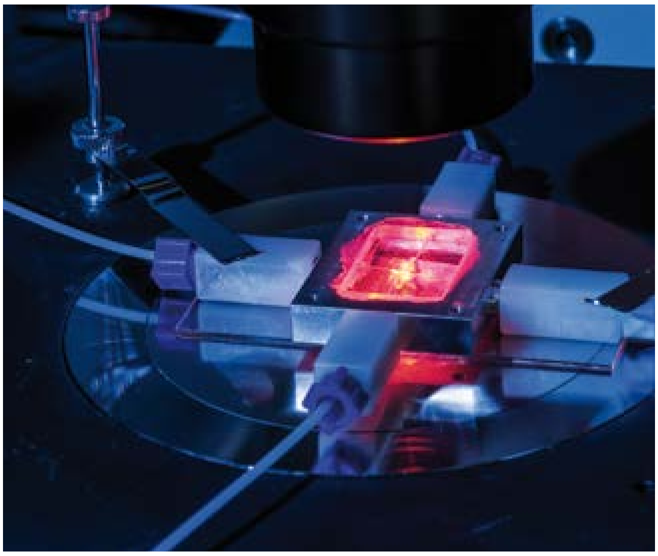
Recently, various experimental groups have succeeded in introducing a single magnetic atom, for example a manganese atom, into a single quantum dot. This is highly interesting, as the spin of this magnetic atom could be used for data storage within the framework of quantum information theory. Unlike the spin of an electron, which can only assume two possible values, the spin of a manganese atom has six possible orientations. As it interacts only very weakly with its surroundings, it has a long lifetime – which makes it attractive for storage purposes, but which also makes any targeted switching in a certain state more difficult.

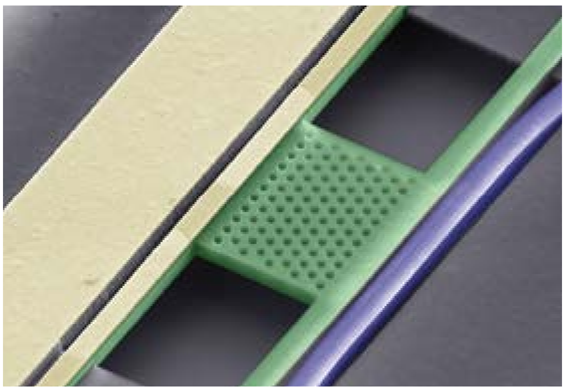
The researchers in Prof. Dr. Kuhn's team have been able to develop switching protocols with which, on a time-scale of some tens of picoseconds, the spin of a manganese atom can be moved into each of the six possible states.

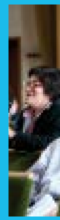
In the process, the quantum dot is irradiated by a suitable series of ultrashort light pulses in order to excite the electrons of the quantum dot and monitor their quantum state. Excited electrons, in turn, can transfer their spin state to the manganese atom. If, at the end, the electrons are returned to their ground state through appropriate light pulses, the manganese spin remains in its new state.

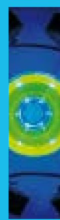


Team meeting with Prof. Dr. Tilmann Kuhn (second from right)







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