Physics

Thin Films, Bright Future

By Hubert Filser

Source: Jan Greune / LMU

LMU physicist Alexander Högele studies ultrathin semiconducting films and carbon nanotubes, which possess astonishing physical properties. He has now received the second highly endowed European Research Council grant in his career.

Exploring new physics is sometimes a simple matter. One can apply a piece of sticky tape to the tip of a pencil, peel it away and with luck an atomically thin sheet made up of a single-layered, two-dimensional lattice of pure carbon will stick to the tape. This is graphene – transparent, ultralight, and extremely tough. A square meter of this marvelous material weighs less than a milligram, and a cat could use the sheet as a hammock without the risk of falling through it. The trick first occurred to Russian physicist Andre Geim. Together with Konstantin Novoselov, he went on to win the Nobel Prize for Physics in 2010 for the isolation and characterization of the properties of graphene.

"It's amazing how much interesting physics one can do with simple tools and a little curiosity. That was a characteristic of the Soviet school of physics," says nanophysicist Alexander Högele, who himself grew up in the Soviet Union, and admires this unassuming approach to innovative materials. His own work focuses on the search for nanomaterials with unusual optical properties, principally with a view to applications in photonics and quantum technologies. In a project funded by the European Research Council (ERC), he and his research group successfully developed ways of fabricating carbon nanotubes made of graphene that exhibit specific and potentially useful optical characteristics.

Visitors to his office at the Faculty of Physics enter a world of quantum effects and highly unusual materials, of 'pseudospins' and 'potential wells'. Högele's goal is to fabricate materials that emit light quanta ('photons') with a specific energy (wavelength) and can be used in photonic applications and perhaps as the basis for quantum communication. "We study functional materials at the atomic scale," he says – nanotubes made of single layers of atoms, and ultrathin 2D semiconductors.

Honeycombs, rolled up

Accounts of the goings-on in the nanoworld often make it sound like a totally unfamiliar cosmos. Researchers who probe the properties of materials like graphene work at the frontiers of physics and encounter effects and phenomena that lie beyond the sphere of classical physics. But it's not always necessary to use high-tech methods to discover new aspects of this unfamiliar world, Högele says.

For some time, his group has been working with carbon nanotubes, characterizing their properties and behavior at temperatures close to absolute zero (-273°C). Nanotubes are optically active, and the wavelength of the light they emit when excited with a laser depends on their diameter. Moreover, the intensity of the light emitted at these very low temperatures is quantized. This meant that they could, in principle, be exploited for the secure transmission of information via optic-fiber cables, as any attempt to eavesdrop on the message would alter the state of the photons and could be detected. The crucial question was whether the system could be coaxed into emitting photons with a specific energy (i.e. frequency) at room temperature.

One promising approach to the problem was to adjust the emission by chemically modifying the nanotubes. The cylinders are several micrometers long and have a diameter of about 1 nanometer. Each consists of a single-layered sheet of graphene rolled up into tube form. However, it is possible to replace some of the carbon atoms that make up the regular honeycomb lattice of graphene, either with atoms of another element or with chemically reactive functional groups. And indeed, this doping strategy allows one to tune the frequency of the emitted photons. "We are now hopeful that we will be able to produce nanotubes that are tailor-made for applications in quantum technology," Högele says.

The primary goal is to create materials that can be used for secure quantum-based communication. "We have already succeeded in modifying the color of the emitted single photons so that they conform to the technical specifications of the existing optic-fiber network,"Högele says, although the signal bandwidth is still too broad. However, using technical tricks, such as optical resonators, it should be possible to improve the quality of the signal and the yield of suitable photons.

The major challenge lies in the fact that the modified nanotubes must function as single-photon sources (SPS) – they must consistently emit single photons of precisely the same optical frequency, and nothing else. If this reliability can be achieved, the route to quantum communication technologies will be open. In addition, atoms or electronic excitation states in semiconducting films, and other quantized properties such as spin states, can serve as information carriers. If ongoing research efforts succeed, we will enter an era in which technology is no longer based on the tenets of classical physics, but on the probabilistic laws of quantum mechanics. As yet, none of these visions has resulted in real devices, and even the laboratory models that have so far been tested leave a lot to be desired. But research in the field has already raised great expectations with regard to future applications of nanomaterials and quantum effects.

Multilayered heterostructures

In parallel with the nanotube projects, Högele's research group has begun to explore ultrathin materials made of elements other than carbon. In terms of their possible use in digital applications, 2D carbon-based systems have one great disadvantage. Graphene is not a semiconductor, and therefore cannot be used to build transistors, which are the key components of conventional electronics. This explains why researchers have turned to other 2D materials, which promise to be more accommodating in this respect. The crucial factor here is the so-called bandgap. In the quantum mechanical picture of condensed-matter systems, this term refers to the difference in energy levels between the so-called valence band and the conduction band in which electrons are mobile.

"We study functional materials at the atomic scale": Alexander Högele in the cleanroom. *Photo: Jan Greune / LMU*

In recent years, the search for ultrathin 2D materials has taken on the character of a gold rush. In particular, compounds containing so-called transition metals, such as molybdenum or tungsten, have aroused great interest. Researchers explore the technological potential of some 500 materials belonging to this class. Many of these are highly reactive or unstable in the presence of air or moisture. Most importantly, when they are investigated as single or stacked two-dimensional layers of atoms, these materials exhibit quite different properties than do the more familiar bulk samples of the same composition. "This is a new research field in solid-state physics," says Högele.

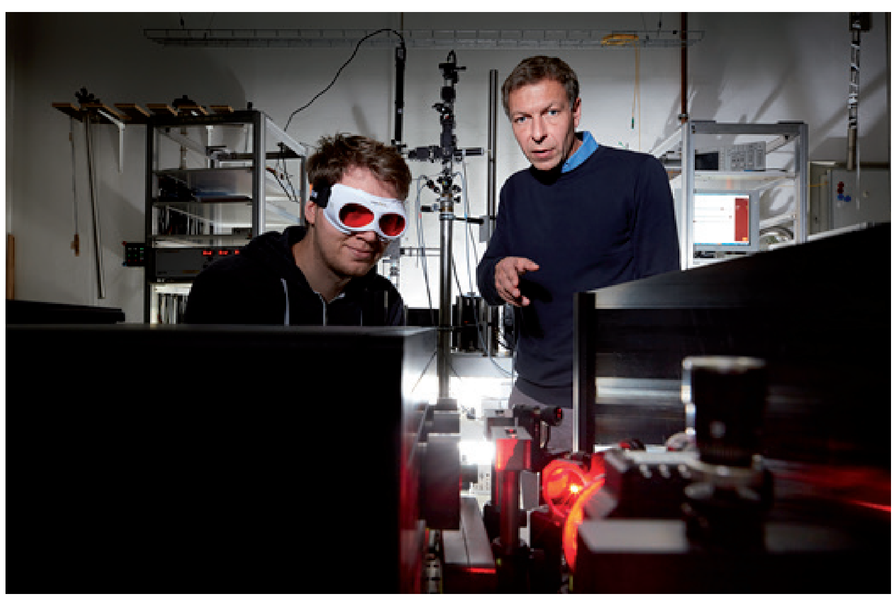
And in this field, he is now working with materials similar to molybdenum disulfide (MoS_2), a new miracle material which can be used to make transistors. Many substances which, like MoS_2, belong to the class of transition-metal dichalcogenides, interact strongly with light, and have great potential for applications in optoelectronics. In many cases, the physical bases for these characteristics are not fully understood. "Even after years of research we are still discovering unexpected phenomena," Högele says. And many of these could be of practical use.

Research

Here again, expectations are high. The prospect of quantum-based opto-electronic information processing has sparked a veritable explosion in research. Many of the effects recently characterized in 2D transition-metal-based systems may serve useful purposes in the future, although Högele cautions that there is a long way to go. He then cites one such unexpected effect, and plunges into the fundamentals of quantum physics. The electrons in 2D MoS2 can be raised to a higher energy level by excitation with polarized light. "Circularly polarized light generates charge carriers that exhibit either right- or left-handed circular motion," Högele explains. "Their associated angular momentum is quantized, and is described by the so-called valley index, which can be detected as so-called valley polarization." The valley index thus constitutes a further degree of freedom that could be used to encode information, and it may even prove to be a useful resource for quantum computing. The temporal evolution of quantum states is another phenomenon, which could perhaps be exploited for parallel processing of information." A whole research field is now devoted to finding ways to make quantum information processing technically feasible," says Högele. Different systems compete with one another to serve as platforms for the implementation of the necessary processing operations, including some based on atoms or ions trapped in optical lattices.

But the emergence of an exciting new area of basic research for physicists represents only the first tentative step. In the world of practical applications, extensive tests are essential to ensure that novel materials behave in precisely predictable ways. This issue is underlined by recent work on the valley index. Independent research groups have measured different levels of valley polarization in what were ostensibly identical semiconducting devices. The deviations are attributed to varying levels of surface defects in the crystals used, resulting from variations in fabrication conditions. "Whether or not fascinating physical phenomena such as valley polarization can be utilized in quantum technologies will depend crucially on the ability to produce sufficiently pure and defect-free crystals," Högele says.

It is not always easy to discern where new discoveries in basic research might lead us. This also holds for another innovative field centered on ultrathin 2D materials. The approximately 500 such materials so far described include not only semiconductors, but also insulators, ferromagnetic and even superconducting materials – in other words the whole spectrum of properties known from work with three-dimensional counterparts. However, because they are so thin, 2D ferromagnetic compounds, semiconductors and superconductors have the considerable advantage that they can be combined with each other at will. By stacking two-dimensional atomic crystals on top of one another, one obtains so-called Van der Waals crystals. These "heterostructures" are held together by very weak forces and, as each new layer is added, the physical properties of the stack can change dramatically. The precise mechanisms behind such effects are not well understood, which opens up another new playground for theorists and experimentalists. "Sometimes attention becomes focused on a particular phenomenon quite by accident," Högele says. His attention has now been captured by tungsten-containing compounds, such as its disulfide and diselenide (WoS2 and WoSe2, respectively) and by hexagonal boron nitride (BN). "At the moment, everyone is playing around, just like Nobel Laureates Geim and Novoselov did with graphene." The enormous variety of intriguing molecules promises to open up a plethora of technological



Tests of optically active nanomaterials: Alexander Högele (on the right) and his coworker Jonathan Förste in the Optical Spectroscopy Laboratory.
Source: Jan Greune / LMU

Research

possibilities. If one can only find the right combination of materials, perhaps one can build components like transistors or even whole circuits in nanoformat. The motivation for these efforts is the hope of reaching the ultimate in miniaturization. "It is astounding to realize how much progress is now being made in quite elementary ways." It is now possible to assemble entirely novel composite materials that have never existed in nature. "There are lots of exciting developments to look forward to," Högele predicts. But then he adds a cautionary tale: The properties of silicon had been investigated in the laboratory for decades before the element became the basis for today's mass-produced electronics. "By that standard, our field is still relatively young."

Dr. Alexander Högele
heads a research group at the Chair for Condensed Matter Physics at LMU. Högele (b. 1975) studied Physics at Heidelberg University and at LMU, where he obtained his PhD. He then held a postdoctoral position in the Institute of Quantum Electronics at the ETH Zürich, before returning to LMU as Junior Professor in 2008. He received a highly endowed Starting Grant from the European Research Council (ERC) in 2013, and has now been awarded an ERC Consolidator Grant

The original article appeared in "Einsichten – das Forschungsmagazin No. 2, 2017", *LMU's German-language research magazine.*
Translation: Paul Hardy,