Isolated from the environment: A new precision laboratory in Stuttgart houses an experimental cabin that optimally blocks out environmental noise, allowing Max Planck researchers to conduct extremely precise investigations into quantum phenomena in nanostructures.

Quantum World **in a Cube**

Nanoelectronics is at once a promise and a challenge. Within their tiny dimensions, electrons, the drivers of electronic circuits, exhibit some exotic quantum effects. Using ultrasensitive techniques, researchers in **Klaus Kern's** department at the **Max Planck Institute for Solid State Research** in Stuttgart are studying the behavior of electrons in nanostructures.

TEXT **ROLAND WENGENMAYR**

People of antiquity were aware that you could impart an electric charge to amber, a fossilized resin, by rubbing it. The ancient Greek word for amber being *élektron*, when a particle with a negative elementary charge was discovered in the late 19th century, it was logical to call it an "electron". We now know that electrons are what hold our world together. As quantum glue, they link atoms to form molecules and molecules to form the astonishing variety of the organic and inorganic world around us. The entire field of chemistry is based on the quantum properties of electrons. Without electrons as carriers of energy and information, society would face a total blackout.

It is thus no wonder that electrons remain a major focus of basic research. That is certainly true of Klaus Kern's Nanoscale Science Department at the Max Planck Institute for Solid State Research in Stuttgart. The behavior of electrons in tiny nanostructures is a topic that pervades the department's entire field of research. The research focuses on basic as well as exotic quantum properties that electrons exhibit in various environments.

RESEARCHERS ARE ABLE TO OBSERVE INDIVIDUAL ATOMS

The scientists explore the peculiar properties of electrons confined within nanostructures by studying individual molecules as well as ultrathin layers like the carbon-based graphene, which could open up myriad new applications for electronic elements (see page 34, *Chips from a Sheet*). The researchers are able to shed light on the behavior of electrons in nanodimensions only because they are able to capture and study individual atoms and molecules. In doing so, they are constantly pushing the boundaries of what is technically feasible.

A single atom is so tiny that its size in relation to a chicken egg is like that of a chicken egg to the planet Earth. It's just a few tenths of a nanometer (one billionth of a meter) in diameter. >

"Nano" comes from the ancient Greek word for dwarf, and if you want to work with such dwarfs, you need the very finest tools – tools that can only be fashioned from atoms. Klaus Kern's department uses tools that are essentially ultrafine metal needles, the tip of which can narrow in extreme cases to a single molecule or atom.

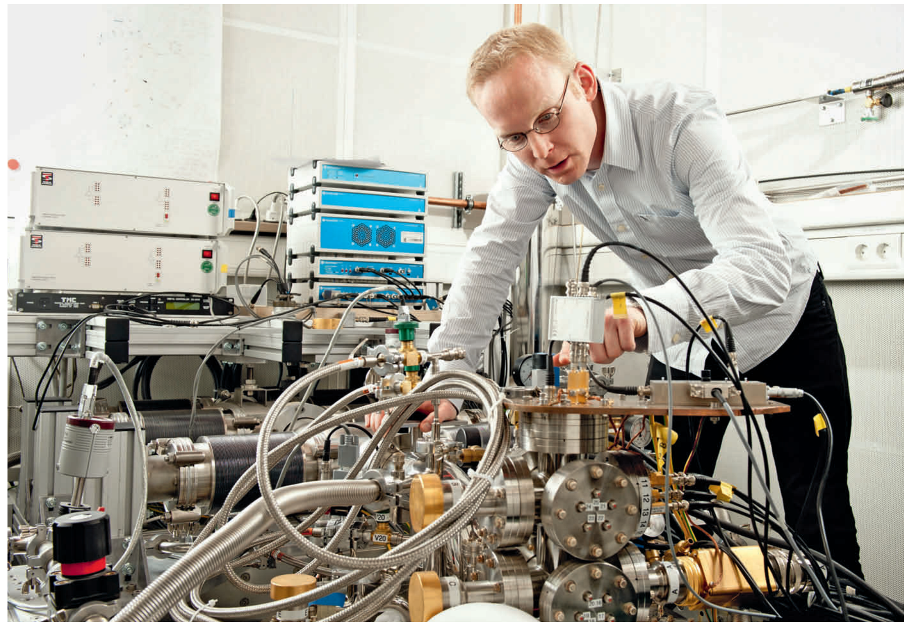
HARD BATTLE AGAINST A NOISY ENVIRONMENT

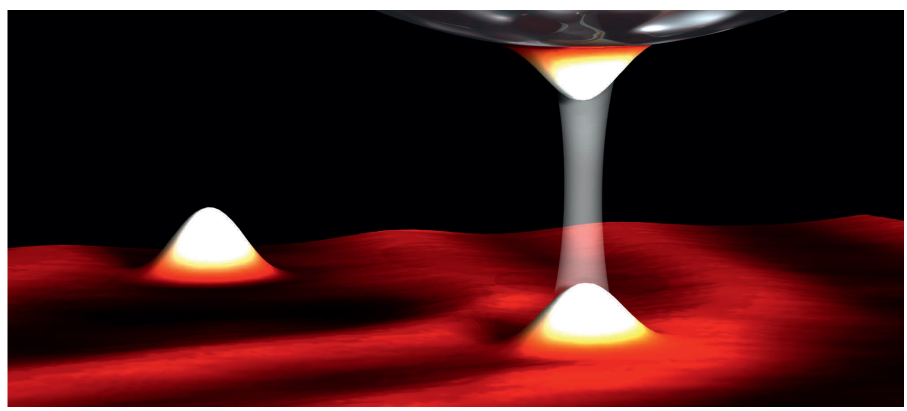
These ultrafine probes are used in scanning tunneling microscopes, instruments that can actually render individual atoms visible. The probes move across a surface, scanning individual atoms as they do so. Information about atomic structure is provided by electrons that manage to cross the vacuum barrier between atoms on the sample surface and atoms on the probe tip. Physicists say that the negative charge carriers "tunnel" through the vacuum zone, which would normally pose an impenetrable barrier.

But capturing individual atoms with supersharp needles means waging a hard battle against an environment full of noise. People who live in old buildings and play vinyl records will be familiar with the problem in a crude form. As you walk over the springy wooden floorboards, the needle hops across the record grooves. The needle of a scanning tunneling microscope reacts to tiny vibrations in the same way, but far more sensitively. An experiment can even be ruined by the public bus that stops a hundred meters away in front of the institute.

Research on two levels: Technician Wolfgang Stiepany adjusts an aperture in a scanning tunneling microscope whose outer vacuum jacket extends through a hole in the ceiling into the floor above. Numerous pumps, compressors and electronic controllers create the necessary conditions for the precision experiments inside the instrument.

Photo: Friedemann Bayer





Keeping a close eye on everything: Christian Ast checks the connections of a scanning tunneling microscope (top). Researchers in the Nanoscale Science Department conduct most of their experiments using such instruments. The principle is always the same (bottom): A tunnel current (illustrated by the transparent bar) flows between an ultrafine tip and a nanostructure placed on a substrate, providing information about the quantum properties of the sample. Here, an atom, which appears as a bright bump, is being studied; the tip of the microscope also tapers to a single atom.

Photos and graphic: Tom Pingel (top), MPI for Solid State Research (bottom)

The scientists in Stuttgart thus have to take great pains to shield their experiments from the outside world. The work of Christian Ast and Markus Etzkorn demonstrates what that means in practice. The two physicists use a highly sophisticated scanning tunneling microscope. Ast and his team started planning and constructing their experiment in 2003, but it wasn't until early 2011, after a scientific marathon full of technical hurdles, that they achieved success. For example, a circular hole had to be hewn into the concrete ceiling of the laboratory for the huge steel column of the outer vacuum jacket to pass through. The instrument, whose inner mechanisms are constructed like a high-tech onion, occupies two floors of the building.

At the core of the instrument, behind multiple layers of cooling jackets and shields, lies the actual scanning tunneling microscope. “The scanning head is about the size of a fist,” Ast explains. Samples are introduced into the innermost chamber of the instrument, which is nearly the only one of its kind in the world, through an elaborate series of airlocks. Since January 2011, the cold maintained inside the instrument is so extreme that even a Siberian winter is hot by comparison. The researchers have come within a few thousandths of a degree of absolute zero, minus 273.15 degrees Celsius. Thermal energy being nothing more than the chaotic motion of atoms and electrons, which would wreak havoc with the experiment, heat must be almost completely banished from the instrument.

The instrument does more than just provide ultrasharp images. At these low temperatures, many metals become superconductors – in other words, they lose their electrical resistance. Superconductivity is a collective quantum phenomenon that binds electrons together in a sort of mass wedding. Electrons form couples, known as Cooper pairs, which then sweep, without dissipation, through the material in a kind of quantum ballet. Despite having been discovered over a century ago, this complex choreography of electrons still poses many unanswered questions.

SUPERCONDUCTIVITY SURVIVES A STRONG MAGNETIC FIELD

One of the questions the Stuttgart-based researchers asked themselves was how superconductivity behaves when it is confined within the tip of a scanning tunneling microscope. To find out, Ast's team used an extremely powerful electromagnet, which is also housed within the onion layers of their instrument. In superconductors, as in a perfect dynamo, magnetic fields generate circular countercurrents. These eddies try to squeeze the magnetic field out of the superconductor. However, if the magnetic field is too strong, superconductivity collapses. “To put it simply, the compensation currents become too strong,” Ast explains. They tear the Cooper pairs apart, so to speak.

As early as 1970, physicists wondered what would happen if superconductivity were constricted too tightly for the eddies to destroy it. They predicted that a strong magnetic field would then pen-

Creating the basis for organic electronics: Uta Schlickum uses a scanning tunneling microscope to study how electrical current flows through individual atoms and molecules. In the background is the ultrahigh vacuum system in which the scanning tunneling microscope is located. The upper part of the apparatus houses a cryostat, which cools the inside of the instrument to temperatures far below the freezing point.

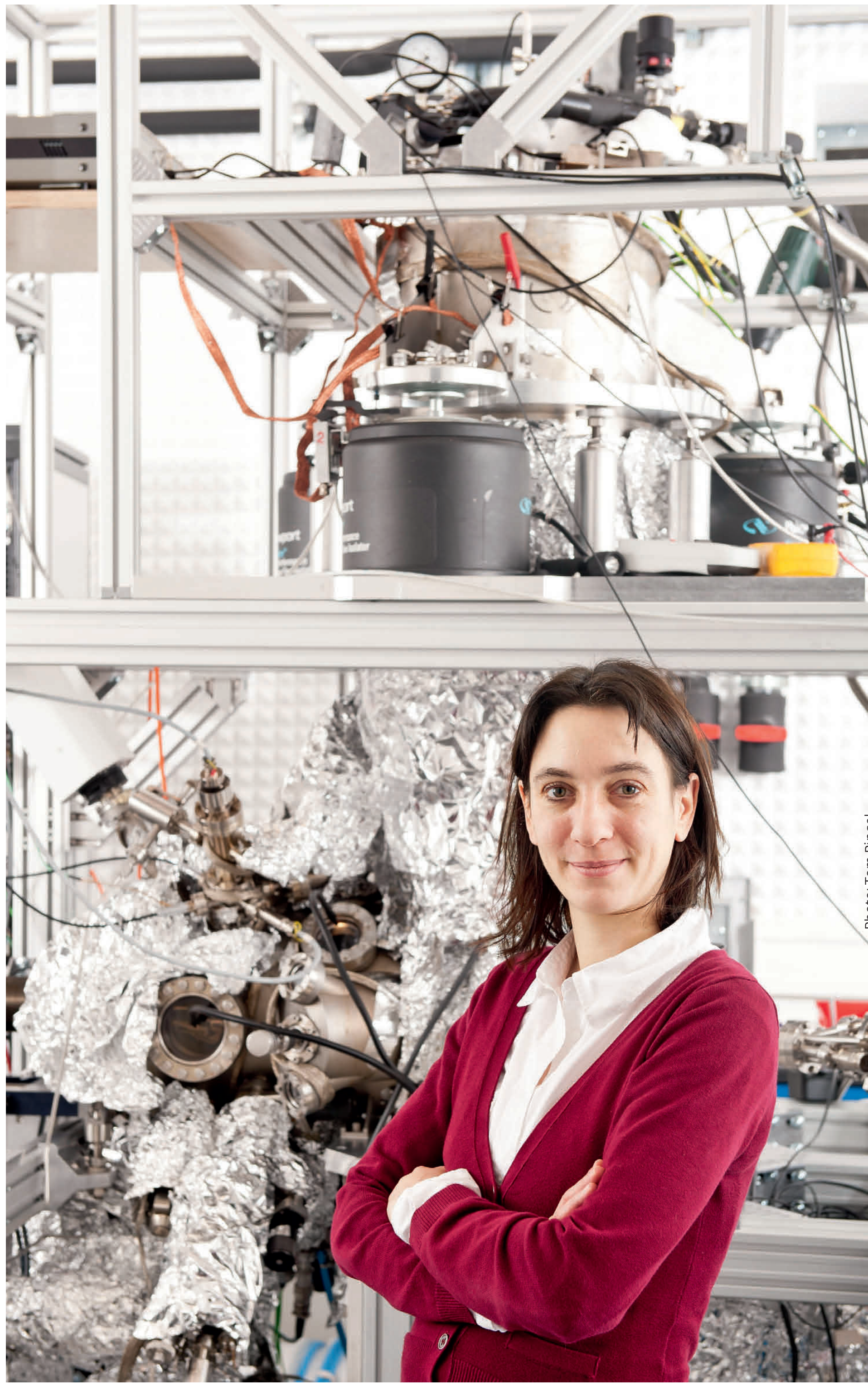


Photo: Tom Pingel

etrate through the superconductor without separating the Cooper pairs. Later experiments actually confirmed this predicted longer lifespan in ultrathin superconducting films. Thanks to Ast's team, we now know that the phenomenon also applies to superconducting tips of scanning tunneling microscopes – knowledge that is important not least for the continued use of superconducting probe tips in experiments today.

EXPERIMENTS FLOATING ON AIR SPRINGS

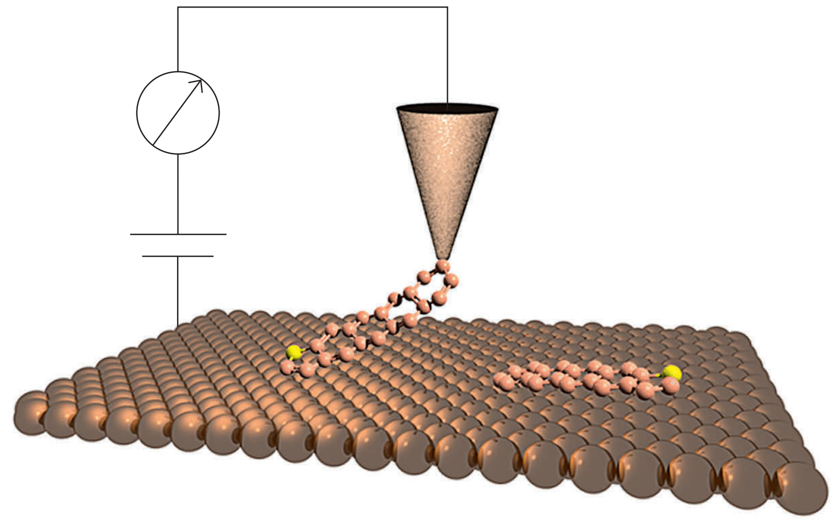
"We will be able to reduce the noise even more when we move into the new precision laboratory," says Christian Ast, with an eye to the future. The architecturally interesting laboratory building, which was inaugurated in 2012, provides an ideally shielded environment for the experiment. The setup is installed in one of eleven house-size cubes within a large hall. To aid identification, each cube is painted a different color, which inadvertently makes the arrangement look like the colorful building blocks of a giant child.

On the upper floor, which floats on air springs, each cube contains a supersensitive experiment. The lower floor, which is almost perfectly isolated from the floor above, houses the necessary infrastructure comprising vibrating vacuum pumps and other interfering equipment. In addition to vibration protection, the cubes are also fitted with sophisticated shielding against electromagnetic radiation, which is ubiquitous in the environment. Once closed, safe-like doors shut out all interference.

One cube contains the scanning tunneling microscope used by Uta Schlickum. "We can pick up a single molecule with our needles or, for example, place a metal atom at a specific location within a molecule, explains the physicist, who heads an Emmy Noether junior research group. Schlickum's tool is a probe tip that culminates in a single metal atom. Using this quantum probe, her team is investigating how electrons flow through a molecule as tiny quantum currents.

For the experiment, a molecule is placed on a nearly perfect copper surface. Copper makes a particularly good substrate because it is an excellent electrical conductor and at the same time isn't chemically aggressive. The latter is important, because the team wants to find out how minor chemical changes to the molecule affect its electrical properties.

"These relationships differ from molecule to molecule," the physicist explains. Recently, the researchers placed pentacene under the probe tip. This molecule is a good organic semiconductor and is therefore a hot candidate as a material for future organic electronics. However, what exactly happens in molecules when electrons flow remains a mystery. Nor is it known how a molecule's properties are altered by chemically attaching metal atoms or smaller molecular building blocks to it.



Electronics taken to extremes: Using the needle of their scanning tunneling microscope, members of Uta Schlickum's team lift a molecule, in this case a pentacene derivative, from a metal surface and measure how much current flows through the molecule at a given voltage. This provides information on charge transport in the individual particles.

A SOLAR CELL THAT CHEMICALLY BREAKS DOWN WATER

The five hexagonal rings of pentacene contain 22 carbon atoms and 14 hydrogen atoms. The correspondingly large number of electrons hampers a precise understanding of the molecule's electronic properties. This is because the behavior of the electrons depends on the quantum states of the molecule, and the more electrons that are involved, the more complex the quantum states become.

The shapes these states take are reminiscent of the long extinct trilobites. Such quantum curves are attractive not only to basic researchers, but to anyone who wants to use these molecules in organic electronics in the future. Organic electronics could facilitate environmentally friendly manufacturing of clothing and packaging equipped with flexible and cheap electronic circuits, light emitting diodes or solar cells.

Future solar cells of a very special kind are a pet project of Soon Jung. The Korean draws two lines and an arrow between them: that's how high sunlight has to make electrons hop up an energy quantum ladder. "We need around 1.4 volts," she says. That's because the solar cells the Korean is researching aren't meant to produce electrical current; lower voltages would be sufficient for that. Instead, the photovoltaic element is designed to split water chemically into hydrogen and oxygen in a highly efficient manner. If hydrogen could be generated on a large scale in this way, it could provide a means of chemically storing renewable energy that would be superior to today's best electrical batteries. After being distributed through a network of pipelines, the hydrogen generated could be used to power fuel cell cars.

For this process to work, every electron in the solar cell that is liberated by sunlight must contribute energy to permit the 1.4 "electron volt" jump. In the molecular world, that's quite a leap. Moreover, the solar cell should make as efficient use as possible of the full spectrum of sunlight. Jung's group is thus studying promising molecular candidates in the hope that light quanta impinging on them will efficiently release electrons with the desired energy. The chemist points out that this is still firmly in the realm of basic research.

A SINGLE PHOTON AT THE PRESS OF A BUTTON

In another cube, Klaus Kuhnke, together with his Ph.D. student Christoph Grosse, is approaching the matter from the opposite direction. The two researchers hope to generate light with electrons – but not just any light. It has been known for some time that the fine needle of a scanning tunneling microscope, together with the smooth metal surface below it, forms a kind of cavity – or at least it has the appearance of a cavity for tunneling electrons.

If the experiment is set up correctly, an electromagnetic wave is generated. It behaves like a vibrating string above a soundboard, explains team leader Kuhnke. The result is a weak light, but one with special properties. Practically any light source produces light quanta, known as photons. The photons are produced randomly, similar to the way in which radioactive nuclei decay. But physicists want to be able to generate one and only one photon whenever they desire – at the press of a button, as it were.

"It's called photon on demand," says Kuhnke, and in recent years, it has been demonstrated by physicists in so-

Graphic: MPI for Solid State Research

phisticated laser experiments. The Stuttgart-based scientist hopes to be able to develop an alternative "quantum lamp," a light source that would be useful in basic quantum experiments. "You could also use it to test the security of transmission lines," the physicist explains, putting the phenomenon in a contemporary context. "If a photon we know has been sent fails to arrive at its destination, we can conclude that there's an eavesdropper on the line."

In information technology, electrons are interesting not only as a light source, but also as carriers of spin. Spin, to use a visual analogy, corresponds to the axis about which an electron rotates, transforming the charge carrier into a tiny elemental magnet. So it could also be visualized as a small magnetic needle. The spin enables a single electron to carry two bits of digital information. One bit is conveyed by the charge of the electron, as in conventional electronics, and another bit by the orientation of the particle's spin – that is, the direction of the magnetic needle.

This idea has given rise to the research field of spintronics, which promises faster and more energy-efficient electronics. The trail in Stuttgart leads to Marko Burghard. The physical chemist and his group are working on two types of materials that are attracting a great deal of attention within the research community: graphene and topological insulators. These materials all share the characteristic of having a superflat two-dimensional electron system.

FUNCTIONALIZATION TRANSFORMS GRAPHENE INTO A MAGNET

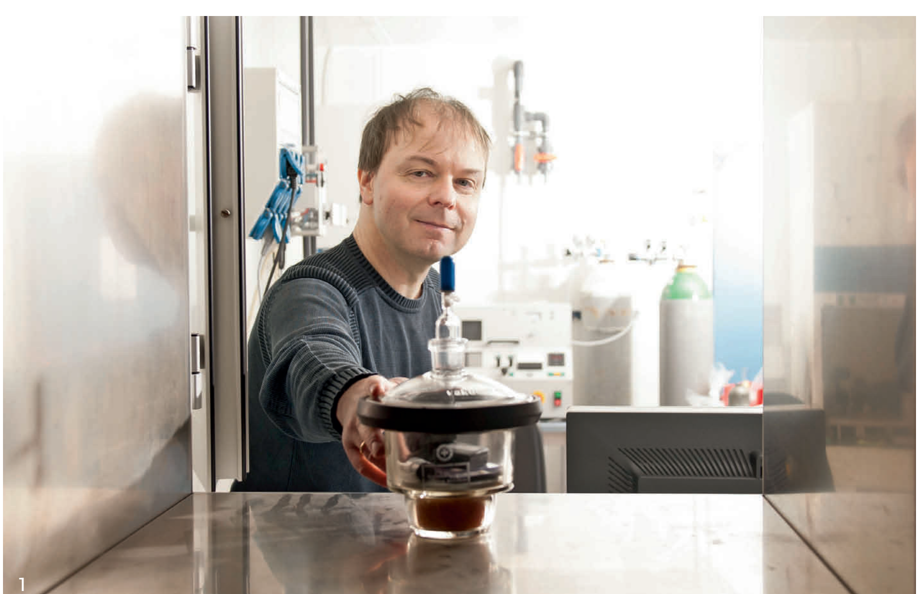
Graphene consists of a single layer of hexagonal carbon honeycombs. Until a few years ago, it was unclear whether such a material could actually exist in a stable state. Graphene flakes, after all, are just one atom thick in one dimension, but macroscopically large in the other two dimensions. Surprisingly, graphene has proved to be highly stable and extremely resistant to tearing.

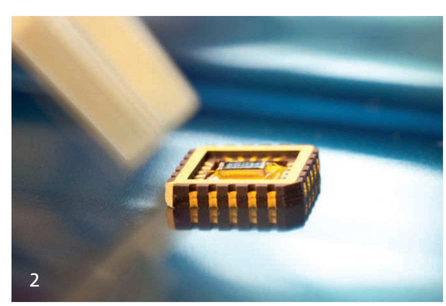
Burghard is particularly interested in the material's electronic properties. In principle, the spin of the electrons flowing in graphene can be directly manipulated. However, to make functioning spintronic components from graphene, it is necessary to chemically attach various molecules to it. This "functionalization" clears the way for building in various switch elements on a graphene substrate. But attaching molecules to the carbon layer is no mean feat: "The problem is precisely the high chemical stability of graphene," says Burghard. Despite this, his group, working in international cooperation, recently demonstrated that it is possible to construct a proper magnet – a ferromagnet – after suitably functionalizing graphene.

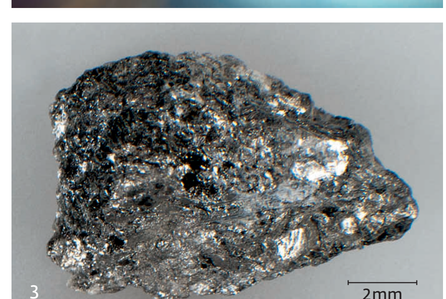
Burghard is even more fascinated by topological insulators than by graphene. These compounds owe their curious name to the fact that they don't conduct any electrical current in their interior – in the third dimension. Yet they are good electrical conductors across their two-dimensional surfaces.

A simple picture helps illustrate the remarkable behavior of these materials. In conductors and semiconductors, electrons in the outermost shells

Marko Burghard is interested in electronic behavior in two dimensions, for example in graphene. He keeps components made of the material in a desiccator to prevent the ingress of dust and moisture (1). Graphene, which serves as the active material, is fitted with electrodes on a substrate and then integrated in a chip carrier (2). Burghard's team is also studying topological insulators, which conduct current only across their surface. The researchers recently discovered that the naturally occurring mineral kawazulite is also a topological insulator (3).







Photos: Tom Pingel (left, top right), MPI for Solid State Research (bottom right)

Tracking down the electronic quirks of the nanoworld: Stephan Rauschenbach, Soon Jung, Klaus Kern and Verena Schendel discuss new experiments (from left to right).

of atoms are responsible for the materials' electrical conductivity, because they are able to break free and travel through the material. In topological insulators, in contrast, the electrons are held captive in atomic orbitals. However, at the surface of the material, the orbitals are truncated, allowing electrons to break free and move about unhindered. An electrical current in this two-dimensional "electron gas" is associated with an electron spin orientation. It is this that makes topological insulators so interesting for future spintronic applications.

The first synthetic topological insulator was demonstrated in 2008. The scientists in Stuttgart even recently discovered that nature itself produces such materials. They found that the natural mineral kawazulite is a topological insulator. "Our sample comes from an old gold mine in the Czech Republic," says Burghard. The researchers were electrified not only by the fact that the mineral occurs naturally; they also found that kawazulite is a perfect topological insulator in the laboratory, despite being full of natural impurities. This shows that the effect is extraordinarily stable.

If you peer over the shoulders of the researchers in Klaus Kern's department, you will learn about the many approaches they are taking to investigate the electronic properties of nanostructures. You will also quickly realize that electrons act radically differently on the nanoscale than on the macroscale, and that they are full of surprises. In particular, the Stuttgart-based researchers aim to expand our knowledge of the often bizarre quantum properties of the nanoworld. But like all good basic research, nanoelectronics has the potential to revolutionize technology in unforeseen ways. Spintronics, organic electronic components and solar cells for sustainable energy supply are just a few of the many conceivable applications. ◂

TO THE POINT

- **Electrons exhibit different properties in nanostructures than they do on the macroscale, and sometimes exotic quantum effects also occur.**
- **To investigate the electronic properties of individual atoms and molecules, researchers at the Max Planck Institute for Solid State Research use scanning tunneling microscopes that are meticulously shielded from any interference such as vibrations and heat and that are among the best in the world.**
- **The quantum effects that occur in nanodimensions could lead to the development of spintronics or single-photon light sources. Thus, they clear the way for new approaches in information processing.**

Photo: Tom Pingel