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Illustration: Schupp / Götz

Strong, Conductive and Defect-Free

Carbon nanotubes are a fascinating material. In experiments at ultra-low temperatures, physicists make their different properties interact with one another – and in so doing find answers to fundamental questions.

Carbon is everywhere. All forms of life are made of organic carbon compounds, and even in its purest natural forms of diamond and graphite we encounter this chemical element in everyday life. Two other carbon modifications have also become well-known outside scientific circles: the fullerenes, the “football-shaped” carbon molecules, and the perfectly flat, two-dimensional material graphene. Graphene became famous in 2010, when Andre Geim and Konstantin Novoselov received the Nobel Prize in Physics for their work on this material.

However, most people are unaware that there is another modifi-

Left: With the aid of electron-beam lithography, structures are “written” on the surface of the chips. Right: Electron microscope image of a freely suspended carbon nanotube; the light metal electrodes and the trenches etched between them are clearly visible. Below: A model nanotube.

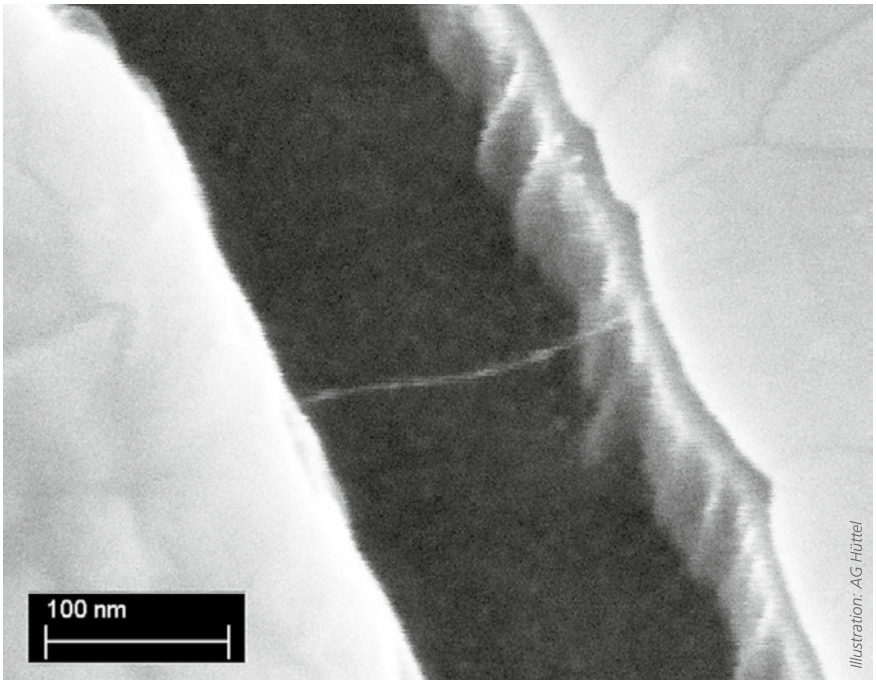


Illustration: AG Hüttel

cation: tube-shaped carbon macromolecules. Scientists have known about them since the 1960s from the results of transmission electron microscopy; in 1993, Sumio Iijima and Donald S. Bethune discovered single-wall carbon nanotubes, where a single layer of graphene forms a quasi-one-dimensional self-contained tube.

Carbon nanotubes have been used in technical applications for many years. They possess very high tensile strength – a property which is exploited in surfboards and bulletproof vests. They can also conduct very high electric currents within an extremely small cross-section, which makes them of interest in chip technology.

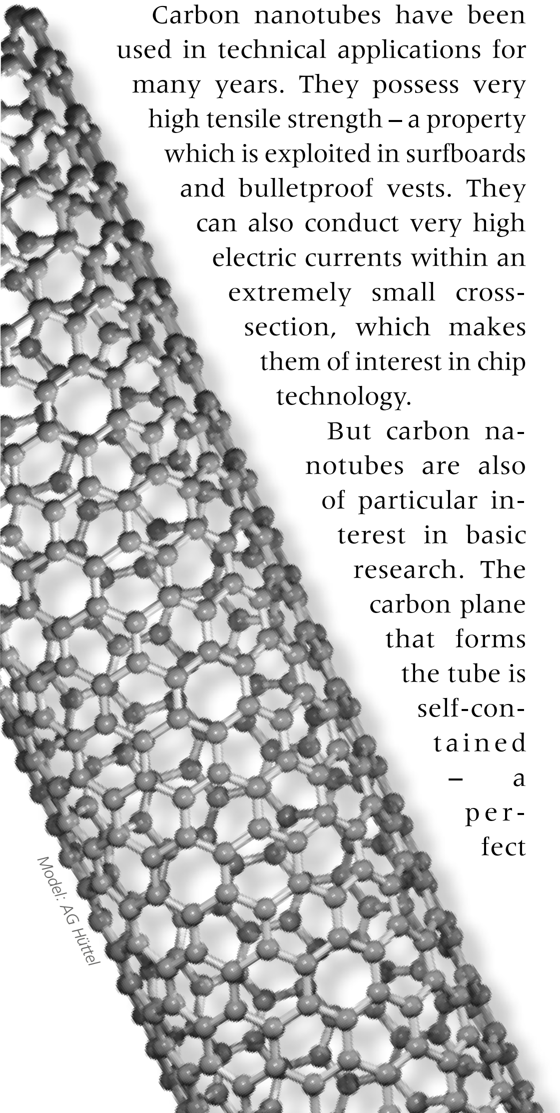
But carbon nanotubes are also of particular interest in basic research. The carbon plane that forms the tube is self-contained – a perfect shape with no uneven, undefined edges to interfere with its electronic or mechanical properties. And if a clean nanotube is allowed to grow across a trench on a chip so that it is freely suspended, it is possible to prevent perturbations caused by contact with the chip surface – creating a system in which the quantum mechanical properties of the nanotube can be observed in high detail.

This particular system is the topic of a DFG-funded Emmy Noether working group at the Institute of Experimental and Applied Physics at the University of Regensburg. Since 2010 the research group has been combining nanoelectronics and nanomechanics at very low temperatures with the aim of realising electronic spectroscopy of carbon nanotubes and demonstrating interactions between the mechanical movement of a vibrating nanotube and the electrons flowing through it as electric charge carriers.

The institute offers the ideal environment for this type of research, with excellent facilities from cleanroom chip fabrication to a helium liquefier as well as close collaboration with other working groups. Researchers at Regensburg also have extensive previous experience with nanotubes. The Emmy Noether group takes advantage of both factors to focus on a fabrication process that maximises the visibility of the nanotube properties.

First, metal electrodes are constructed on a chip and trenches are formed between them. Nanotubes are then allowed to grow chemically over the trenches. The nanotubes then cover the electrodes, bridging the approximately 1 micrometre wide space between them. This technique keeps the macromolecules absolutely clean and undamaged; no further fabrication steps can introduce defects or contamination.

If the chip is then cooled to a temperature of a few hundredths



Model: AG Hüttel

of a degree above absolute zero, the thermal energy of the environment is so low that it is insufficient to charge the nanotubes with a single electron, the smallest unit of electrical charge. The electrons already captured on the nanotube form quantised states similar to the shell of an atom, which is why these systems are also known as quantum dots or "artificial atoms". By applying a gate voltage, the number of trapped electrons can be externally influenced; current will only flow through the nanotube if the number of captured charges can change, through "single electron tunnelling", the passage of one single electron after another.

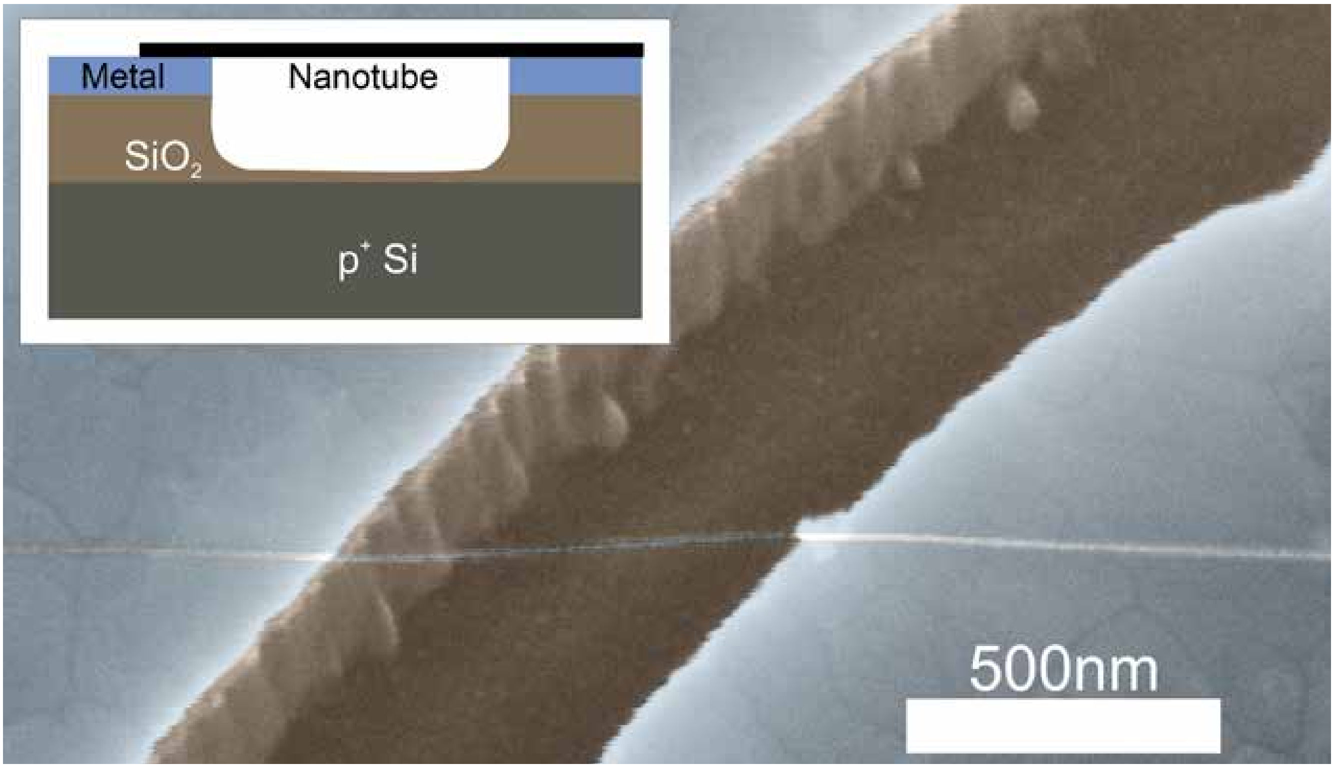
Quantum dots are found in many semiconductor materials. What is special about carbon nanotubes is the fact that they are free from defects and have a clearly defined geometry. With a tube diameter of around one thousandth of a micrometre, the electrons can be aligned as if strung out on a line, in a perfect lattice of carbon atoms repeated along the entire length of the freely suspended nanotube. If this system is gradually charged with one electron after another, the development of the spectrum of this captured charge system can be tracked using electrical measurements starting from the first electron – from the ground and excited states of an individual particle to complex multi-particle effects.

Concentration required in the laboratory: Physicists Daniel Schmid and Stefan Blien prepare the low-temperature apparatus for further measurements.

Illustration: AG Hüttel

When a freely suspended nanotube is viewed in a scanning electron microscope, the picture instantly reminds you of a guitar or piano string, or, in the case without mechanical tension, a skipping rope. Just like these everyday objects, and in addition to its electronic properties, a carbon nanotube can mechanically vibrate. Particularly at very low temperatures such as are used by the Emmy Noether group in the experiments in Regensburg, this vibration is almost free of mechanical damping. If a piano string had similarly low damping, a note would continue to sound for several minutes after the key was struck! If a direct current is applied to the nanotube, spontaneous self-excitation can occur; the nanotube starts to vibrate without being periodically driven. This effect is so marked that it sometimes interferes with electronic spectroscopy measurements as mentioned above.

But the electronic properties also influence vibration – particularly when we remember that current is carried by individual electrons with discrete charge. Researchers at the Technical University of Delft and elsewhere have demonstrated that electrons can also "transport" vibration energy directly out of the nanotube. The team in Regensburg has discovered that even a relatively small magnetic field causes eddy currents and therefore a damping of the movement – what could be



A delicate carbon nanotube bridges a trench etched on the chip. The graphic model can be seen top left.

called the world's smallest eddy current brake!

So why is all this so interesting to researchers? For one thing, there are still many unanswered fundamental questions relating to purely electronic systems. What effect does the detailed rolling-up of the graphene-like carbon plane to form a nanotube have on the electron states? Can we identify the exact type of the nanotube by examining the available measurement data? How do the electrons interact as the charge on the nanotube is increased? Other intriguing questions and research approaches emerge when carbon nanotubes are combined with ferromagnetic or superconducting materials. For example, researchers are seeking to control the electron spin, i.e. the intrinsic angular momentum of electrons, which is responsible for many magnetic effects and interactions. One objective of this field of research – known as spintronics – is information processing based on magnetism and not just electrical charges as in conventional computer systems.

Finally, in terms of mechanical effects, the transition from classical physics to quantum mechanics is an extremely topical area of research. To approach this transition requires a very high vibration frequency, which presents no problem for carbon nanotubes with their combination of high tensile strength and low mass. In addition, a very low temperature is required to prevent thermal excitation. Detecting and controlling the mechanical vibration of such a system without using a powerful external drive signal and therefore causing it to heat up is another challenge currently being tackled by a number of research groups throughout the world.

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