Electrons confined inside nano-pyramids

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Quantum dots are nanostructures of semiconducting materials that behave a lot like single atoms and are very easy to produce. Given their special properties, researchers see huge potential for quantum dots in technological applications. Before this can happen, however, we need a better understanding of how the electrons "trapped" inside them behave. Dresden physicists have recently observed how electrons in individual quantum dots absorb energy and emit it again as light. Their results were recently published in the journal "*Nano Letters*".

Quantum dots look like miniscule pyramids. Inside each of these nano-pyramids are always only one or two electrons that essentially "feel" the constricting walls around them and are therefore tightly constrained in their mobility. Scientists from Helmholtz-Zentrum Dresden-Rossendorf (HZDR), TU Dresden and the Leibniz Institute for solid State and Materials Research Dresden (IFW) have now studied the special energy states of the electrons trapped inside individual quantum dots.

Sharp energy levels

The behaviour of electrons in a material essentially determines its properties. Being spatially constrained in all three spatial dimensions, electrons inside a nano-pyramid can only occupy very specific energy levels – which is why quantum dots are also called "artificial atoms". Where these energy levels lie depends on the chemical composition of the semiconductor material as well as the size of the nano-pyramid. "These sharply defined energy levels are exploited, for example, in highly energy-efficient lasers based on quantum dots. The light is produced when an electron drops from a higher energy level into a lower one. The energy difference between the two levels determines the colour of the light," Dr. Stephan Winnerl of HZDR explains.

Seeing electrons inside individual quantum dots

The researchers in Dresden working with Dr. Winnerl were recently the first to succeed in scanning transitions between energy levels in single quantum dots using infrared light. Although, they could only do this after overcoming a certain hurdle: While the pyramids of indium arsenide or indium gallium arsenide form spontaneously during a specific mode of crystal growth, their size varies within a certain range. Studying them with infrared light, for example, one obtains blurred signals because electrons in different sized pyramids respond to different infrared energies. This is why it is so important to obtain a detailed view of the electrons trapped inside a single quantum dot.

The scientists approached this task with the special method of scanning near-field microscopy. Laser light is shone onto a metallic tip less than 100 nanometers thick, which strongly collimates the light to a hundred times smaller than the wavelength of light, which is the spatial resolution limit for "conventional" optics using lenses and mirrors. By focusing this collimated light precisely onto one pyramid, energy is donated to the electrons, thereby exciting them to a higher energy level. This energy transfer can be measured by watching the infrared light scattered from the tip in this process. While near-field microscopy involves major signal losses, the light beam is still strong enough to excite the electrons inside a nano-pyramid. The method is also so sensitive that it can create a nanoscale image in which the one or two electrons inside a quantum dot stand out in clear contrast. In this fashion, Stephan Winnerl and his colleagues from HZDR, plus physicists from TU and IFW Dresden, studied the behaviour of electrons inside a quantum dot in great detail, thereby contributing towards our understanding of them.

Infrared light from the free electron laser

The infrared light used in the experiments came from the free electron laser at HZDR. This special laser is an ideal infrared radiation source for such experiments because the energy of its light can be adjusted to precisely match the energy level inside the quantum dots. The laser also delivers such intense radiation that it more than makes up for the unavoidable losses inherent to the method.

"Next, we intend to reveal the behaviour of electrons inside quantum dots at lower temperatures," Dr. Winnerl says. "From these experiments, we hope to gain even more precise insights into the confined behavior of these electrons. In particular, we want to gain a much better understanding of how the electrons interact with one another as well as with the vibrations of the crystal lattice." Thanks to its intense laser flashes in a broad, freely selectable spectral range, the free electron laser offers ideal conditions for the method of near-field microscopy in Dresden, which benefits particularly from the close collaboration with Prof. Lukas Eng of TU Dresden in the scope of DRESDEN-concept.

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