June 22, 2000

Quantum Dots and Quantum Rings Behave Like Atoms

Many Innovative Applications Begin to be Envisioned

Santa Barbara, Calif.--In 1993 Pierre Petroff's solid state research group at the University of California at Santa Barbara (UCSB) developed the techniques to self-assemble quantum dots. Since then quantum dots and a related nanoscale structure called quantum rings have turned into a research industry with findings published in an average 200 papers per year.

The latest article "Optical Emission From a Charge-Tunable Quantum Ring," published in the June 22 issue of Nature by researchers in Petroff's UCSB group and their Munich collaborators, is the first to report precise spectroscopic measurements of a single quantum ring.

Essentially, a semiconductor quantum dot or ring is a region of material a few nanometers in size where the carriers are confined. These carriers can be electrons, holes (missing electrons), or excitons (bound electron-hole pairs).

The charge carriers are confined in a nanoscale box or in a donut-shaped ring of one semiconducting material (in the case of the reported research, Indium Arsenide). That box or ring is surrounded by another semiconducting material (Gallium Arsenide in the reported research) which presents a potential barrier to the motion of the carriers out of the box.

In the quantum mechanical world of the atom, negatively charged electrons orbit around a positively charged nucleus, but the electrons can only exist at fixed distances from the nucleus, and their energies are themselves fixed or discrete. In the quantum mechanical world, the energy of the carriers is quantized.

Researchers call quantum dots and quantum rings "artificial atoms" because the charge carriers in them behave the same way that orbiting electrons behave around the nucleus of an atom. In other words, the charge carriers in quantum dots or rings both can absorb or emit discrete amounts of energy as atoms do.

The development of quantum rings in Petroff's group opened the possibility of exploring the properties of these donut-shaped quantum dots.

The precise measurements of a single quantum ring reported in the Nature paper prove that quantum rings indeed behave as artificial atoms. Heretofore, Petroff's UCSB group had made such measurements for large collections (millions) of quantum dots or rings so that the findings could have been understood as an averaging. Measurements of a single quantum ring by the Munich group provide the definite proof of the "atom like" behavior of the quantum rings. In addition, the Nature paper reports detection of the emission energy of excitons to which various numbers of electrons have been added. Their energies are quantized.

Petroff points out, "There are four aspects to this kind of study: (1) controlling the growth of the quantum dots or rings, (2) controlling the shape of the resultant structure (whether quantum dot or quantum ring), (3) studying the physics of these structures through spectroscopy, and (4) making functional devices. Petroff's UCSB group engages in research on all four aspects. And his European collaborators focus on several aspects of the spectroscopic analysis.

What can be done with quantum dots and quantum rings?

First, quantum dots and quantum rings provide another approach to making lasers. The key idea behind lasers is that the light emitted is coherent and has a fixed wavelength. In principle, said Petroff, all quantum well lasers, such as those in CD players, could be replaced with quantum dot lasers.

But the big advantage that quantum dot lasers have over customary quantum well lasers is less sensitivity to temperature variations. So quantum dot lasers are better suited for use, for instance, in airplanes which are subjected both to hot ground and also freezing high-altitude temperatures. More than one start-up company is now gearing up to sell quantum dot lasers, according to Petroff.

Other uses for quantum dot devices include infrared and photo detectors. Another possible application is a quantum dot memory device. "The basic principle," said Petroff, "is to shine light to write the information by separating the electrons and holes in adjacent quantum dot layers. Then applying an electric field gets the hole to recombine with an electron to produce light for reading the memory element.

"There is also quantum computing," said Petroff, "which operates on a paradigm very different from the present transistor-based computing. Quantum dots, because of the discreteness of the carriers' energies, may provide a quantum mechanical way of encoding information."

Despite all the tantalizing, potentially transformative practical applications of quantum dot and quantum ring research, what really grabs Petroff's imagination is "the basic physics that is very fascinating."

One of the next big challenges is to repeat all of the experiments done heretofore but to substitute Gallium Nitride as the semiconductor box and Aluminum Nitride as the surrounding material. Gallium Nitride is the new semiconducting material, developed by Petroff's UCSB colleague Shuji Nakamura around the same time that Petroff's group was developing quantum dots.

Why switch to Gallium Nitride? "Because," said Petroff, "all of these applications so far work well only at low temperature. The challenge is to have them work well at room temperature, and that is the promise of the Gallium Nitride-Aluminum Nitride matrix."

In addition to Petroff, who is a professor of materials and of electrical and computer engineering, the authors of the Nature paper include his UCSB graduate student Winston Schoenfeld and Jorge Garcia, formerly a UCSB postdoctoral fellow. The European-based collaborators include R.J. Warburton, C. Schäflein, D. Haft, F. Bickel, A Lorke, and K. Karrai. Their work was done at the Centre for Nanoscience and Sektion Physick at Ludwig-Maximilians-Universität in Munich, Germany. Warburton, the article's first author, is at Heriot-Watt University i n Edinburgh, Scotland.

Images

Media Contact

Tony Rairden
trairden@engineering.ucsb.edu
805.893.4301
