

The logo for 'cientifica' features the word in a white, lowercase, sans-serif font. A small, stylized graphic of a yellow and orange flame or spark is positioned above the letter 'i'.

QUANTUM DOTS

Technology White Papers
nr. 13

The background of the cover is a dark field filled with numerous small, brightly colored spots in shades of purple, blue, green, yellow, and red. These spots are arranged in a way that suggests they are being viewed through a microscope or a similar optical instrument, with some spots appearing as vertical streaks, possibly due to motion blur or the way the light is being captured. The overall effect is a vibrant, multi-colored pattern against a black background.

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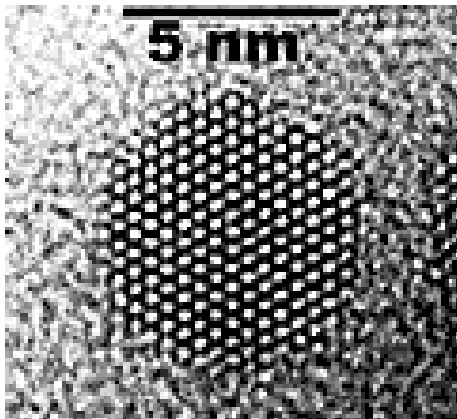
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Origin of content

The free reports in this series are extracted from the technology reports that make up the Nanotechnology Opportunity Report collection and are designed to offer an introduction to the variety of technologies that fall under the nanotechnology umbrella. The full reports also include 'opportunities' sections, covering the various applications of the technology and their effects on markets, and a list describing the companies involved in the technology.

Quantum dots

Introduction to quantum dots



*TEM image of a quantum dot.
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Quantum dots sound very exotic and indeed they are, in terms of the way they work, which is dictated by the rules of quantum mechanics. Effectively, a quantum dot is something capable of confining a single electron, or a few, and in which the electrons occupy discrete energy states just as they would in an atom. Quantum dots have been called artificial atoms, in fact, and the ability to control the energy states of the electrons by applying a voltage has led to the exotic idea of a material whose chemical nature could be modified at will, making it emulate different elements, such as lead one minute then gold the next—effectively programmable matter. Fanciful as

such ideas seem, they are in fact quite straightforward, although the precision required to make such materials is currently beyond our reach, but only just.

There are three major fabrication methods for quantum dots.

One approach involves growing quantum dots in a beaker. This approach was pioneered by Louis Brus in the late 1970s when he was at Bell Labs, and carried on by some of his post docs, notably Paul Alivisatos and Mounji Bawendi. Originally, the quantum dots grown were semiconductors such as cadmium selenide or cadmium telluride, but now people have made quantum dots of nearly every semiconductor and also of many metals (gold, silver, nickel, cobalt, to name a few) and insulators as well. The semiconductors have the fascinating property that their color depends on the size of the dot, thus it is possible to use one chemical substance and yet make structures with a wide variety of colors simply by varying the size of the dot. The metal dots have been shown to have a range of interesting electrical, magnetic and catalytic properties. The architecture of these chemically-grown dots is getting very sophisticated, with onion-like structures formed by coating one material with another becoming more common. These structures can be used to shield a chemically- or electrically-sensitive dot from an unfriendly environment. The semiconducting dots are finding use in biological imaging applications (for example by the company

Quantum Dot), and magnetic metal dots show promise as recording media (being pursued by IBM).

The two other approaches create quantum dots at or near the surface of a semiconductor crystal. Originally, such quantum dots were formed by growing a semiconductor heterostructure (a plane of one semiconductor sandwiched between two others). If the sandwiched layer is thin enough, about ten nanometers or less, electrons can no longer move vertically in a classical fashion—they are effectively trapped in that dimension. Such a structure is called a quantum well. Quantum wells generate photons of very specific wavelengths and can be found in lasers used in laser pointers or key rings. Imagine now taking a thin slice through this material to create a very narrow strip of the sandwich. The electrons are trapped in a second dimension. This is a quantum wire. Quantum wires can make lasers that are switchable at very high speeds and can be used as wave guides. Now rotate ninety degrees and do the same again; the electrons are now constrained in all three dimensions and you have a quantum dot. The electrons now have nowhere to go and start to behave just as they do in an atom, where they are similarly restricted.

In the early method a lithographic process was used to create a two-dimensional structure that could then be etched down to isolate a quantum dot. However, these quantum dots were only nanometer scale in one dimension—the thickness of the semiconductor layer used to trap the electrons in the dot. The other two dimensions were typically limited by the resolution of the lithography, and could be as big as a micron. This meant that electrical studies performed on these dots had to be carried out at extremely low temperatures (thousandths of a degree above absolute zero), to freeze out thermal effects.

Later (the third method), researchers began to grow "self-assembled" dots by depositing a semiconductor material with a larger lattice constant (essentially a figure representing the distances between the atoms in an ordered crystalline structure) onto a semiconductor with a smaller lattice constant (this is called strained epitaxial growth). Typical systems were germanium on silicon and indium arsenide on gallium arsenide. It is these self-assembled dots that have been used to fabricate quantum dot lasers. In January 2002 a Toshiba research group grew indium phosphide quantum dots on a p (positive) semiconductor layer then applied an n (negative) layer on top. The result was a device capable of generating single photons. A similar approach was used to create a single photon detector.

Semiconductor quantum dots fluoresce at very precise frequencies, stimulated either electrically or by a wide variety of wavelengths, so that they absorb light of one frequency but continue to emit at the specific frequency dictated by their size. Therein lie some potential applications (see below). The particles also reflect, refract and absorb light in ways that can be affected by an applied voltage, offering potential in photochromic and electrochromic materials (ones that change color with the application of light or electricity respectively), as well as in solar cells.

Additionally, the spin of an electron in a quantum dot can be used to represent a quantum bit, or qubit, in a quantum computer. Though there are other approaches to

quantum computing, such as that demonstrated recently by IBM (using a chain molecule with seven atoms, the spin of which could be controlled by nuclear magnetic resonance, to perform a basic calculation), the quantum dot approach looks the most likely to be scalable in the end to the manufacture of quantum computers.