Quantum Dots for Sale

FEATURE

by Jennifer Ouellette

Artificial atoms illuminate biotechnology and other fields

Nearly 20 years after their discovery, semiconductor quantum dots are emerging as a bona fide industry with a few start-up companies poised to introduce products this year. Initially targeted at biotechnology applications, such as biological reagents and cellular imaging, quantum dots are being eyed by producers for eventual use in light-emitting diodes (LEDs), lasers, and telecommunication devices such as optical amplifiers and waveguides. The strong commercial interest has renewed fundamental research and directed it to achieving better control of quantum-dot self-assembly in hopes of one day using these unique materials for quantum computing (Figure 1).

Semiconductor quantum dots combine many of the properties of atoms, such as discrete energy spectra, with the capability of being easily embedded in solid-state systems. "Everywhere you see semiconductors used today, you could use semiconducting quantum dots," says Clint Ballinger, chief executive officer of Evident Technologies, a small start-up company based in Troy, New York.

Sometimes called artificial atoms, quantum dots fall into the category of nanocrystals, which include quantum rods and nanowires. They are technically defined as small semiconductor crystals containing a variable number of electrons that occupy well-defined, discrete quantum states. However, "the only real requirement for something being classified as a quantum dot is that the object is small enough," says physicist John Venables of Arizona State University, a pioneer in growing crystals on surfaces. Because of their tiny size, quantum dots behave according to the rules of quantum physics, which describe the behavior of atoms and smaller particles, rather than those of classical physics, which describe the behavior of objects consisting of many atoms.

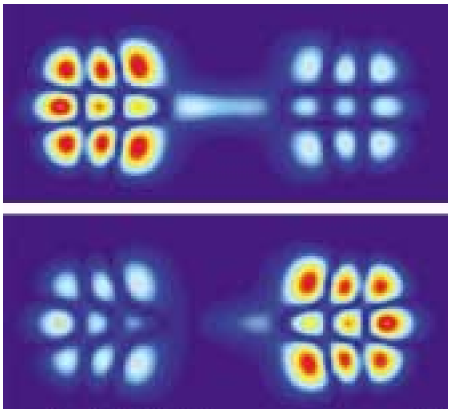
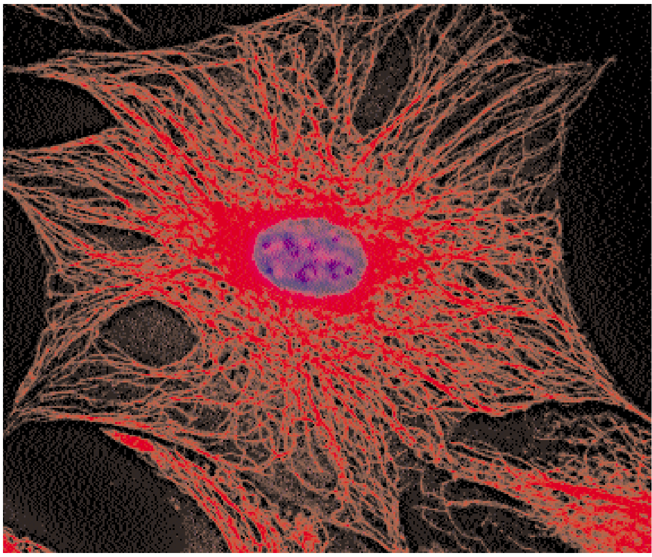

Arizona State University

Figure 1. Two quantum dots connected by a wire behave somewhat like atoms in a molecule, with different energy levels, a property that might be useful as a switch in a quantum computer.

Quantum dots form when a thin semiconductor film buckles under the stress created when its lattice structure differs slightly in size from that of the material on which it is grown, explains Jerry Floro, a researcher at Sandia National Laboratories (Albuquerque, NM). Pressures generated by deposing new layers force the flat film to separate into dots. These dots pop up into the third dimension to relieve the stress rather than continuing to grow against resistance in two dimensions. This extra dimension, combined with the dots' minute size, gives them electrical and nonlinear optical properties different from those of the original thin film—most notably, the emission of light. Quantum dots can also be produced by colloidal synthesis, commonly called "wet chemistry."



The two manufacturing methods have different applications, says Venables. For example, currently it is only possible to connect electronics to epitaxially grown quantum dots. So this method is used predominantly for areas such as telecommunications, logic circuits, and quantum-computing work. But many biological and optics applications, such as LEDs and tunable lasers, do not require such connections. Therefore, quantum dots formed by colloidal synthesis dominate these sectors, particularly because that process is easier to scale up.

Scaling up the colloidal manufacture of quantum dots—which until recently have only been produced in microgram quantities—is critical to their further commercialization, says Steven Talbot, Evident's vice president of marketing. The company currently produces several grams a week, but it needs to develop improved processes to reach kilogram quantities. "There is a difference between what you need to do to make the manufacturing process suitable for commercialization and what you can do in the lab for scientific purposes," notes Brian Korgel, an assistant professor of chemical engineering at the University of Texas at Austin. "You need long-term stability and shelf-life, and a lot of these materials are still fragile. So there are issues of chemical robustness. Also, some applications require self-assembly, and we need to do that reproducibly."

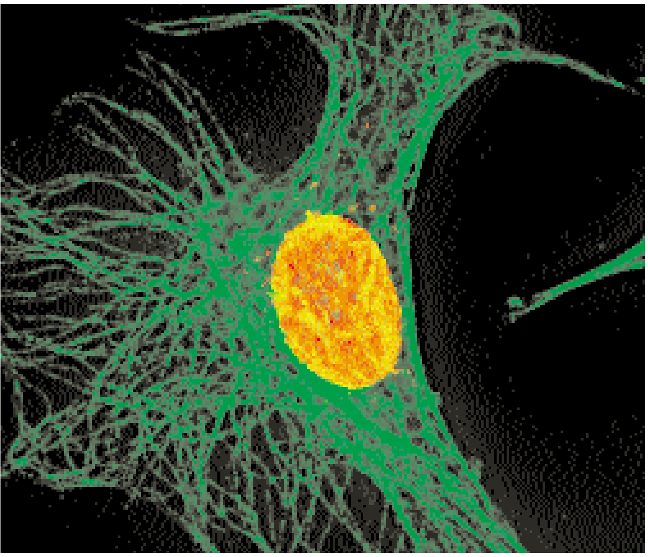

Xingyong Wu, Quantum Dot Corporation

Figure 2. In the cells at left, the microtubules were stained with 605-nm fluorescent quantum-dot conjugate, and the nuclei were counterstained with Hoechst dye (blue). In the cell at right, the nucleus and microtubules were labeled with red and green quantum-dot conjugates, respectively.

Biotechnology

Scale-up issues are one reason that quantum dots found their first commercial applications in biotechnology. "Making quantum dots on scales required for use in devices for photonics or telecommunications would require hundreds of kilograms of material, and existing manufacturing processes cannot do that yet," explains Charles Hotz, director of chemistry for Quantum Dot Corp. (QDC) in Hayward, California. "Biotechnology requires comparatively trace amounts of materials, although they need to be very high quality."

Current biosensors use fluorescence-based dyes, but these dyes emit light across a broad spectral width—which limits their effectiveness to a small number of colors—and they also degrade over time under the microscope. Quantum dots can be fine-tuned to emit at different wavelengths simply by altering the size of the dot. Thus, dots can be used to label and measure several biological molecules simultaneously. And because quantum dots are crystals instead of organic molecules, they remain almost completely stable under the microscope. QDC launched its first nanobiotech product in December 2002: semiconductor quantum dots attached to a biomolecule (streptavidin) for use in cell and tissue analysis. The company plans to market three or four more products within the next few months, each with an affinity for a different molecule, such as immunoglobulin C (Figure 2).

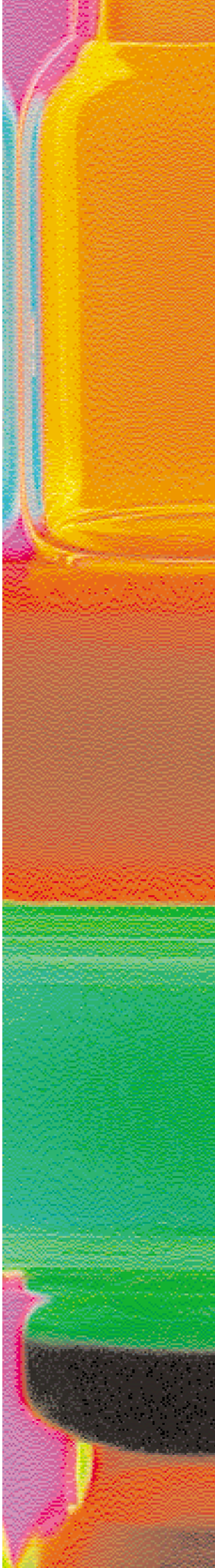
Another application uses quantum dots as inorganic fluorescent probes to shed light on cellular processes, such as the forming or breaking of chemical bonds, which, until now, researchers have viewed only briefly and dimly with the aid of organic dyes. In collaboration with Genentech, Inc. (South San Francisco, CA), QDC is developing products to fill this niche. QDC recently announced that it had successfully labeled breast cancer cells with quantum dots, which can also be used to color-code other kinds of cancer cells. QDC hopes to extend the emission range of quantum dots into the near-infrared.

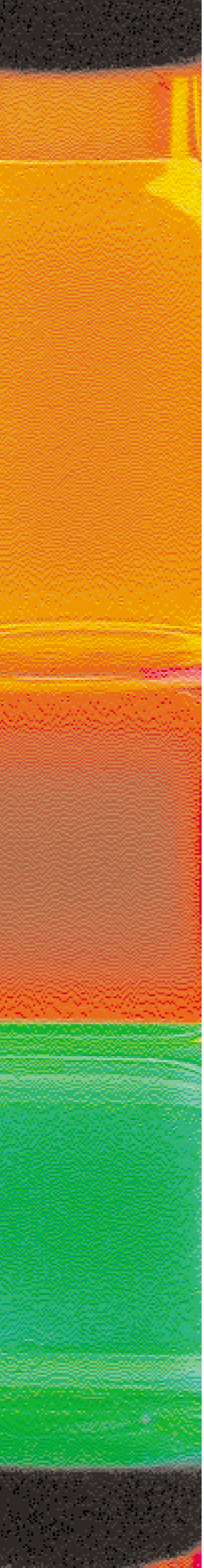
QDC and Evident Technologies both manufacture quantum dots from cadmium selenide, cadmium sulfide, cadmium telluride, lead selenide, lead sulfide, and lead telluride, as well as from hybrid structures that give the dots additional useful properties. Evident plans to release its initial product line later this year for use as biological reagents for immunoassays and DNA and antibody tests. It also intends to target other markets in biotechnology as well as cosmetics and solar cells. And the Department of Defense has expressed interest in using quantum dots for portable biowarfare detection devices. "We are trying to fit our products into existing markets so that we do not have to reeducate our client base or build an entire market sector from scratch," says Talbot of Evident's strategy (Figure 3).

Although Korgel's start-up company, Innova Light, has no product on the market yet, he says that he and some University of Texas colleagues are using silicon-based quantum dots to make selective electrical contacts to neurons. "The idea is that you optically pump a nanocrystal to create an electrical field in the particle, which interacts with the electrical field of a nerve cell, and then combine it with microelectronics technology," says Korgel. Attaching quantum dots directly to receptors on cell surfaces eliminates the need for external electrodes and enables the precise counting and mapping of neurons. One day, this molecular-recognition approach may allow the attaching of specific dots to specific neurons to remotely control neural functions—such as muscle movement in people with certain neurological diseases—by activating selected neurons. Korgel is also investigating making composites of living cells and quantum dots, in which the dots are activated by light to trigger, for example, a drug-delivery application.

LEDs, tunable lasers

Researchers at the Massachusetts Institute of Technology and Los Alamos National Laboratory have demon-





strated that semiconducting quantum dots can provide the necessary efficient emission of laser light for the development of novel optical and optoelectronic devices such as tunable lasers, optical amplifiers, and LEDs. Quantum dots perform well across a wide temperature range and can be tuned to emit at different wavelengths. It is already possible to make LEDs from quantum dots that are precisely tuned to blue or green wavelengths, says physicist Howard Lee of Lawrence Livermore National Laboratory (LLNL). Quantum-dot LEDs could be used to emit white backlight in laptop computers or as internal lighting for buildings. They might also be key to important technological advances in full-color flat-panel displays, ultrahigh-density optical memories and data storage, and chemical and biological sensing.

Realizing that potential requires gaining better control over the creation of quantum dots. Floro's team at Sandia developed novel probes in 1999 that uncovered a repulsion effect between dots that may hold the secret to controlling their formation. The researchers made real-time measurements of atoms clustering to form large three-dimensional dots, called islands, and observed how mutual repulsion caused the dots to change shape and self-assemble as they grew.

Floro and his collaborators also developed another tool to examine dots. They made measurements that treat dots as the originators of light-interference patterns. Because the intensity and direction of light vary depending on the size, shape, and spacing of the quantum-dot islands, they could observe what happened to the islands as temperature, material composition, and stress changed. "This showed us what controls dot evolution and how process conditions such as temperature and strain enhance or suppress dots," says Floro. He uses silicon-germanium in his experiments—although it is not a good laser emitter—because it is a simpler material from which to derive the applicable physics. "We next need to find how much of what we have learned will apply to real laser materials such as gallium arsenide," he says. "If we can understand the fundamental physics, we can ultimately make better quantum dots."

Telecommunications

The availability of tunable semiconductor quantum-dot lasers opens possible applications in the telecommunications industry, especially because dots are also promising materials for making ultrafast all-optical switches and logic gates. "The properties of semiconductor quantum dots offer great potential for optical amplifiers at telecommunication wavelengths," says Frank Wise, a researcher at Cornell University. "The synthesis of quantum dots in glass hosts, for example, is naturally compatible with optical-fiber technology, and polymer hosts might even be acceptable to the industry in the future."

Among other advantages, photonic chips based on quantum-dot lasers would be less expensive and more efficient than current telecommunication lasers, and one could either fit more lasers on the same chip sizes as today or create smaller chips. Researchers at LLNL have demonstrated quantum-dot switches and logic gates that operate faster than 15 terabits/s. The Ethernet, by comparison, can handle only about 10 megabits/s.

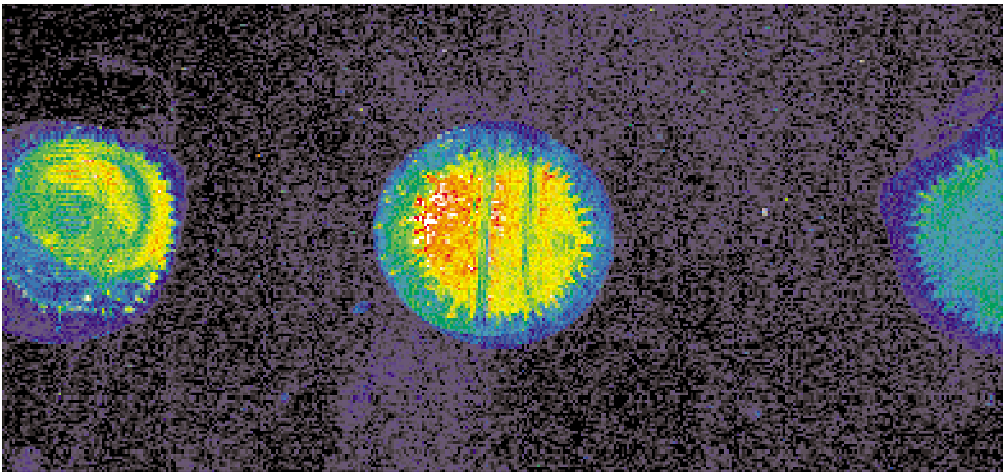
Wise's group is collaborating with scientists at Corning, Inc. (Corning, NY), to develop rudimentary devices from IV–VI quantum-dot materials such as lead sulfide and lead selenide, which have stronger effects of quantum confinement. Their energy gaps also fall naturally into the near-infrared range of 3- to 4-μm wavelengths. When the structure is quantum-confined, the result is materials with optical transitions at 1- and 2-μm wavelengths, the target range for most telecommunication applications. As a first step toward an amplifying-device structure compatible with optical fiber, Corning scientists have made a waveguide that contains lead sulfide quantum dots.

However, commercial telecommunication applications are unlikely to emerge in the next few years because of the industry's investment in entrenched technologies, such as indium phosphide lasers and erbium-doped amplifiers. "We are not realistically going to make something to supplant erbium-doped amplifiers tomorrow," says Wise. "Many issues must be resolved before quantum-dot-based devices can compete with the existing technology." More significantly, the industry has struggled in recent years in an increasingly adverse economic climate. "I do not think the issue is the technology but more the general issues confronting the telecommunications market today," says Talbot. "The industry just isn't investing in new lasers, switches, or optical routers, and that has driven down demand for new kinds of technology."

Quantum computing

Unlike conventional computation, quantum-dot-based quantum computers would rely on the manipulation of electron spin to carry information and perform computations. In 2001, Albert Chang, a professor of physics at Purdue University, and his colleagues linked two quantum dots in such a way that they could control how many electrons were in each dot and then detect the electrons' spins—critical information for quantum computing. The researchers achieved this by creating extremely fine circuits with electron-beam lithography. They coated gallium arsenide with a plastic and then etched fine lines into the plastic, which they filled with a metal. The plastic was dissolved, which left behind metal lines about 50 nm wide. Chang's group is now working both to detect the spins on each dot and to precisely control them.

Last year, Floro's group at Sandia and Robert Hull's group at the University of Virginia serendipitously discovered how to form a unique fourfold quantum-dot molecule—four dots bound together elastically by a hollow



Evident Technologies

Figure 3. Fluorescent reagents (EviBead Fluors) detect 10-µM biotinylated oligonucleotide spots on an aminosilane slide, using false color (white, saturated; red, bright; blue, dull; black, no fluorescence).

core that holds the structure together like glue. This finding has garnered considerable interest from the quantum-computing field as an ideal structure for building quantum-cellular automation. “For example, you would put electrons in two of the dots to represent one logic state, and then force the electrons to switch into the opposite two dots to represent a different logic state—essentially the 1s and 0s used in today’s computers,” says Floro. “We certainly have not demonstrated working quantum-cellular automata, but it is a useful prototype structure, formed entirely by self-assembly and manipulation of the growth kinetics.” Despite these advances, “I doubt you will see quantum computers within five years,” says Floro. “We are still learning about the relevant quantum physics; being able to adequately control the physics to self-assemble true computer circuitry is some time off.”

Ideally, researchers would like to sufficiently control growth to self-assemble a computing element along with the near-field wiring required to attach it to working devices on nanometer size and length scales. That will require a combination of manipulating the thermodynamics and growth kinetics—more control than researchers can achieve now—and cutting-edge lithography techniques. The working concept is to etch with today’s lithographic capabilities and then use the resulting pattern to hierarchically direct subsequent self-assembly at a smaller scale. “By placing structures lithographically on the substrate, and then using the features we have created at one length scale, we can shrink down to the next length scale through self-assembly onto a template structure,” explains Floro. “Achieving that would be a major breakthrough.”

Exactly where quantum dots will find their biggest commercial breakthrough remains to be seen, but the initial biotech applications will surely pave the way for others. And for those engaged in their sale and manufacture, there is no denying their market potential. “I think we are on the verge of a commercial breakthrough similar to what polymers did to the plastics industry,” says Talbot. “This material has so many different uses that it could be a fundamental new material system for a whole host of products that touch on almost all major areas of modern life.” Ω