SPECIAL REPORT

Quantum dots go large

A small industry could be on the verge of a boom, reports **Katharine Sanderson**.

Nanocrystals called quantum dots have promised to revolutionize display technologies, solar power and biological imaging for more than a decade. Yet the quantum-dot market has remained small, with a handful of companies selling dots directly to researchers, using the particles to develop their own products or licensing their technologies to partners.

"Quantum dots have been around for quite a while, but they're taking a really long time to mature," says David Hwang of the market-analysis company Lux Research in New York. A key barrier is price: quantum dots can cost anywhere from US\$3,000 to \$10,000 per gram, restricting their use to highly specialized applications.

But industry analysts are now predicting extremely rapid growth for the market over the next few years, driven by demand for energy-efficient displays and lighting, and enabled by cheaper, more efficient manufacturing processes. In September 2008, market-research company BCC Research of Wellesley, Massachusetts, predicted that the market for products relying on quantum dots would grow from \$28.6 million in 2008 to \$721 million by 2013, with particularly rapid growth in the optoelectronics sector from 2010 (see graph).

Dots by the kilo

Most commercially available quantum dots have a semiconductor core, often a mixture of cadmium and selenium, measuring about 2–10 nanometres in diameter. This core is surrounded by a shell, usually of another semiconductor material, and an outer polymer or inorganic layer.

The small size of the dots gives them unique properties. Photons hitting a dot excite an electron from the semiconductor material, leaving a positively charged 'hole': this electron-hole pair is called an exciton. In a bulk semiconductor, excitons can have a range of energies within a continuous band. But in the nanoscale dots, excitons occupy distinct, quantized energy states. This means that as each excited electron recombines with a hole, it emits a photon with a specific, predictable wavelength. Smaller dots give off blue light, whereas larger dots of the same material appear red.

Although quantum dots were initially made using expensive techniques borrowed from the computer-chip industry, most dots are currently made by 'wet' chemistry methods, such

There's gold at the end of this rainbow.

as squirting hot solutions of organometallic reagents into a solvent. But scaling up this technique — essential for reducing the cost of quantum dots — has been troublesome, because it is harder to maintain the right temperature in larger volumes.

Quantum-dot company Nanoco, based in Manchester, UK, may have an answer. The company, which was spun out of the group of chemist Paul O'Brien at the University of Manchester in 2004, has developed a lower-temperature batch process that uses small seed molecules to grow kilograms of dots from a solution of reagents. And Voxel, based in Beaverton, Oregon, has begun trialling a continuous production process, which can manufacture kilogram quantities a week of most quantum dots for less than \$10 per

gram, according to chief executive George Williams.

The first commercial application of quantum dots took off in 2002, when the Californian nanotech startup Quantum Dot Corporation launched its first quantum dot bioimaging agent. Chemical groups attached to the outside of the dots can hook onto particular cells, for example, giving a useful glowing tag to track the cells' movement. Several different sizes of dots emitting various colours can be used to track multiple cellular processes at the same time.

Bioimaging could receive a boost from recent research that offers a solution to a long-standing yet poorly understood problem. Some quantum dots, particularly those prepared by wet chemistry, tend to blink on and off at random. Last month, Todd Krauss at the University of Rochester, New York, and his colleagues announced that they had managed to eliminate blinking by blending the boundary between a core of cadmium, selenium and zinc, and a shell composed of the latter two elements (X. Wang *et al. Nature* 459, 686–689; 2009). Krauss thinks that non-blinking particles may be a decade away from large-scale manufacture, and it is also unclear whether the discovery will apply to other quantum dots. But if it does, "the field will take a fairly substantial leap forward," he says.

Even though bioimaging generated plenty of business for quantum-dot developer Evident based in Troy, New York, the company is branching out into using its dots to fine-tune the colours of light-emitting diodes (LEDs). The dots absorb a relatively wide range of wavelengths produced by the LED, while emitting light in a much narrower range, producing very

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SOURCE: BCC RESEARCH

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specific colours. The company already sells decorative strings of quantum-dot LEDs in colours from cranberry to tangerine.

Meanwhile, Michael Edelman, Nanoco's chief executive, says that a backlight for flatscreen televisions that relies on the company's dots should be on the market in about 18 months. It will combine red, green and blue quantum-dot LEDs that are more efficient and emit less heat than conventional backlights, he says.

And QD Vision of Watertown, Massachusetts, is about to enter the commercial lighting market. The company was spun out of the Massachusetts Institute of Technology in 2004 by five academics, including electrical engineer Seth Coe-Sullivan, who is now chief technology officer, and Mouni Bawendi, who helped to develop the wet-chemistry method of creating cadmium-based quantum dots (C. B. Murray, D. J. Norris and M. G. Bawendi *J. Am. Chem. Soc.* 115, 8706; 1993).

QD Vision teamed up with Nexxus Lighting in Charlotte, North Carolina, to produce quantum-dot LED lights suitable for commercial and domestic lighting. Unveiled in early May, the lights combine the efficiency of LED

lighting with the warmer colour of incandescent bulbs, says Dan Button, chief executive of QD Vision. He hopes that the lights will provide an energy-efficient alternative to incandescent or halogen lamps, without producing the harsh white light of fluorescent bulbs and conventional LEDs, which often deters consumers. The company expects to begin shipping the lamps, which will cost between \$50 and \$100, by the end of this year.

This kind of collaboration is a common trend in the market, says Hwang. "A lot of these companies are leaning heavily on large corporations to do development and incorporate them into their products," he says.

Shining light

Solar power could also benefit from the tiny dots. Researchers are starting to use them in solar concentrators — flat plates that channel light from a large area and concentrate it onto a solar panel. Organic dyes have already been used in the concentrators to absorb and re-emit light, which then bounces through the plate until it hits a solar cell mounted on the edge.

But dyes are not good at harvesting the red

light in sunlight and are prone to degradation over time. Quantum dots are more robust, can collect light from the far-red and ultraviolet ends of the spectrum, and are also better at capturing the diffuse light of cloudy days. But Amanda Chatten, who is developing solar concentrators at Imperial College London, says that she struggles to buy quantum dots that perform efficiently.

And price is still a significant barrier. "At the moment, quantum dots are about a thousand times more expensive per gram than organic dyes," says Chatten. For a commercially viable solar concentrator, she says that quantum-dot prices will need to drop by a factor of between 100 and 1,000.

Yet despite the global economic downturn, businesses are optimistic. On 1 May, Nanoco started trading on the London Stock Exchange AIM market and has seen its share price rise from £0.21 to £0.56 as of 8 June. Edelman says that the company is busy completing a new, large-scale production facility in Manchester, with a second plant planned in Asia. "If this market is going to take off," he says, "we'll need a lot of material." ■