

from the environment, and could have applications in powering a wide range of nanodevices and nanosystems, especially networks of sensors that are distributed over a large (and sometimes remote or hostile) geographic area⁸. There will also be applications in the defence industry because military sensors and surveillance devices generally need to remain hidden and often have to be located in unfavourable (for example, dirty, wet or subterranean) environments that are unsuited to alternative approaches such as solar energy. Another promising application area is in the emerging field of

implantable biosensors with telemetry for continuous monitoring of various medical conditions. Although nanosensors that could be implanted in the body are already available, their utility is limited by the lack of miniature power sources that have practical lifetimes and do not contain toxic chemicals.

So what is the next step forward for this area? Increasing the efficacy of energy conversion is a must for practical applications. Integration into micro- and nanosystems, and harvesting sufficient power without increasing the overall size will also pose engineering challenges.

However, the self-powered energy-harvesting strategy being pioneered by the Georgia Tech group is an important step forward in the effort to make such devices a practical reality.

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NANOCRYSTALS

Shedding new light on silicon

Experiments in magnetic fields suggest that defects are responsible for light emission from silicon nanocrystals. However, when these defects are passivated with hydrogen, quantum effects become responsible for the emission.

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Silicon is the material on which the numerous electronic gadgets that dominate our lives — from laptop computers to iPhones — are based. Even though silicon has wonderful electronic properties, and has even been labelled as ‘God’s material’, it has poor optical properties, which is why other semiconductors are preferred for devices such as light-emitting diodes and lasers. Unlike bulk silicon, however, nanostructured silicon can actually emit light with reasonable efficiency, although the origins of this photoluminescence have been the subject of intense debate for almost two decades. This debate has focused on whether the quantum confinement of electrons and holes in structures that measure just a few nanometres is responsible for the light emission, or if atomic-scale defects at the surfaces of the nanocrystals are responsible¹.

On page 174 of this issue Manus Hayne and co-workers² report on measurements in high magnetic fields that allow them to distinguish between these two different mechanisms. As often happens in life they find that both processes play a role, depending on the treatment of the nanocrystals. Moreover, they show that it is possible to make one mechanism, and then

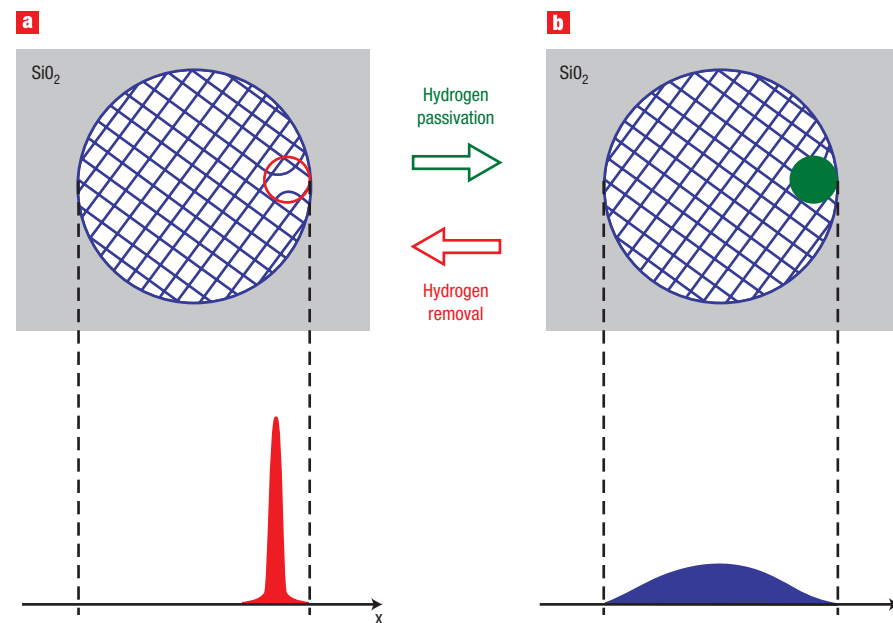


Figure 1 Photoluminescence from silicon nanocrystals embedded in silicon dioxide. **a**, The presence of a defect (circled in red) near the surface of the nanocrystal results in excited electrons being localized in space (bottom). **b**, After hydrogen passivation is used to make the defect electronically inactive, the electrons are no longer localized by the defect, but quantum effects confine them within the nanocrystal (bottom). Ultraviolet radiation can be used to remove the hydrogen, causing the electrons to be localized at the defect again.

the other, the dominant source of light in these materials.

The specific spatial arrangement of silicon atoms, and the resulting electronic

band structure, prevents efficient light emission from bulk silicon crystals. When an electron in an excited energy state falls back to its ground state, it cannot simply lose

energy by emitting a photon — it also needs to lose momentum by exciting vibrations of the crystal lattice. This is what makes silicon a bad optical material, and has frustrated efforts to combine electronics and photonics on one silicon chip.

The most convenient way to investigate light emission from silicon nanocrystals is to excite them with ultraviolet radiation and then observe the photoluminescence at lower energies (that is, longer wavelengths). In 1988 Shoji Murukawa and Tatsuhiro Miayato³ of Kyushu Institute of Technology were the first to demonstrate fairly efficient photoluminescence in the visible range from silicon nanocrystals embedded in insulating silicon dioxide — an arrangement similar to that studied by Hayne and co-workers. Because the emitted visible light had a much higher intensity and higher energy than that expected from bulk silicon, which should be very weak and in the infrared region of the spectrum, Murukawa and Miayato attributed the emission to the effects of quantum confinement.

This early paper was largely ignored. A few years later, however, reports that simple electrochemical etching of crystalline silicon in hydrofluoric acid leads to porous nanostructures that also show efficient light emission at visible wavelengths^{4,5} created huge interest among scientists and engineers. Thousands of papers on light emission from nanoscale silicon structures have been published since then^{1,6,7}, but the origins of the

photoluminescence remained controversial. Numerous indirect experiments produced results in favour of either the quantum-confinement or surface-defect model. Now Hayne and co-workers at Lancaster University, the Katholieke Universiteit Leuven, Albert Ludwigs University in Freiburg and the University of Antwerp are the first to show in, a clever experimental setup, that both mechanisms are present and contribute at a level that depends on the history of the samples².

The basic idea behind the latest experiments is that the electronic states associated with the two mechanisms have different spatial contributions (see Fig. 1). In the case of the quantum-confinement mechanism, the excited electrons are smeared out over the whole nanocrystal, which can be between about 3 and 5 nm across, whereas in the defect model they are localized around the defects at the surface on a length scale of much less than 1 nm.

The spatial extension of electronic states can be probed by looking at the effect on the photoluminescence of extremely strong pulsed magnetic fields at a temperature of 85 K. Hayne and co-workers measured the light emission from as-grown silicon nanocrystals embedded in silicon dioxide as a function of magnetic field strengths up to 50 Tesla. They found that the electronic states were localized to length scales below 1 nm, which suggests that defect states are the dominant source of the

photoluminescence. The nanocrystals still emitted light after they had been exposed to a hydrogen plasma, which is a common treatment for passivating defects and making them electronically inactive, but further magnetic field experiments show that the electronic states then extended over the whole nanocrystal, as happens in the quantum-confinement model. Subsequent heating by a laser drove out the hydrogen and reactivated the defect-related light emission.

The experimental results by Hayne and co-workers clearly favour the defect mechanism for light emission from as-prepared silicon nanocrystals. As this appears to contradict earlier results that favoured quantum confinement effects, the debate of the origins of the photoluminescence from silicon nanostructures is sure to continue. In the meantime, the technological quest for silicon-based light sources will go on unabated^{8,9} independent of what the detailed mechanism of light emission from silicon nanocrystals might be.

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NANOBIOTECHNOLOGY

Putting cobalt on the menu

Nanocrystals of magnetite in magnetic bacteria are known for their high chemical purity, but recent work shows they can be doped with cobalt. This finding could pave the way for the biosynthesis of magnetically tailored nanoparticles.

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What do bones and teeth have in common with mollusc shells and sea-urchin spines? They are all products of biomineralization¹ — a widespread phenomenon that involves the selective uptake of elements from the environment and their incorporation as minerals into functional structures in living organisms².

One of the most remarkable examples of this phenomenon is the internal compass that allows so-called magnetic bacteria to swim along the Earth's magnetic field lines. The compass needle is typically a chain of about a dozen or so sub-100-nm magnetite (Fe₃O₄) crystals, each enclosed inside a membrane (Fig. 1). Obviously driven by the advantage that these bacteria gain from magnetic navigation, evolution has optimized these so-called magnetosome chains on three hierarchical levels: at the material level, by synthesizing a strongly magnetic compound; at the level of the building blocks, by precisely controlling

the crystal size and shape to maximize the effective magnetization per magnetosome; and at the architectural level, by arranging the magnetosomes in a chain to maximize the magnetic dipole moment per cell. There are variations in magnetosome morphology among the different species of magnetic bacteria³, but the remarkable consistency among cells of a given species suggests that there is an underlying genetic blueprint. Indeed, a number of genes involved in controlling these properties have been identified in recent years⁴.

The magnetite crystals in the magnetosomes are of amazingly high