conditions experienced by charge carriers inside the quantum dot.

Photoluminescence spectroscopy has become a standard tool for characterizing neutral quantum dots that do not contain magnetic dopants: in these experiments a laser creates an excited electron–hole pair, also known as a neutral exciton, which almost immediately recombines back to the ground state, emitting a photon in the process. The resulting photoluminescence spectrum is particularly simple, because there are relatively few initial and final states and, moreover, some transitions are forbidden by 'selection rules' that enforce conservation of angular momentum.

Things get more complicated when a Mn dopant is included in the quantum dot, because the exciton can now interact with the five outermost electrons in the 3*d* shell of the Mn atom. Each of these electrons carries a spin of 1/2 in quantum units, and they invariably align themselves so that the total spin, *S*, has a value of 5/2. A measurement of *S* along any direction, for example the *z* axis, must yield a quantized result having one of six possible values: S_z = +5/2, +3/2, +1/2, −1/2, −3/2 and −5/2. This leads to a splitting of the once-simple photoluminescence spectrum into six equally spaced components[10].

Léger's experiment[1] takes the logical next step, by adding an electron or hole and observing how the photoluminescence spectrum changes. By now the system may seem hopelessly complicated: the quantum dot contains one Mn atom (with five 3*d* electrons), one electron–hole pair (the exciton created by the laser), and the extra electron or hole (from gating or resonant optical excitation). But simplification is possible. Consider a negative quantum dot containing one extra electron and one Mn atom. In much the same way that the five 3*d* electrons of the Mn atom align to form a single $S = 5/2$ spin, the extra electron and the electron from the exciton lock together with their spins pointing in opposite directions to form a single $S = 0$ object, which has no magnetic interactions with the Mn atom. Hence for the initial state of the system one need only consider the interaction of the hole with the Mn spin. After recombination, there is just one electron interacting with the Mn spin. The picture is equally simple for a positive quantum dot containing one extra hole and one Mn atom.

The bottom line of the analysis is straightforward: the six-line spectrum should be split by the presence of an additional electron or hole into 12 distinct lines, less one that is forbidden by selection rules. These 11 lines can be seen clearly in the beautiful spectra recorded by Léger and co-workers (Fig. 1). Moreover, by measuring the spacing between lines, they show that the electron–Mn and hole–Mn interactions are affected by the confinement of the charge carriers inside the quantum dot just as expected theoretically. Such manipulation and detection of single electrons on an individual atom within a quantum dot are important steps towards the writing and reading of digital information at extremely small scales.

No one knows for certain what nanotechnologies will exist another hundred years from now. Feynman's famous dictum 'there's plenty of room at the bottom' will someday drive us further down a winding road that already includes oil drops and quantum dots. And if history is any guide, using single electrons to manipulate and detect other electrons will doubtless play a central role along the way. We can only marvel at where we're heading.

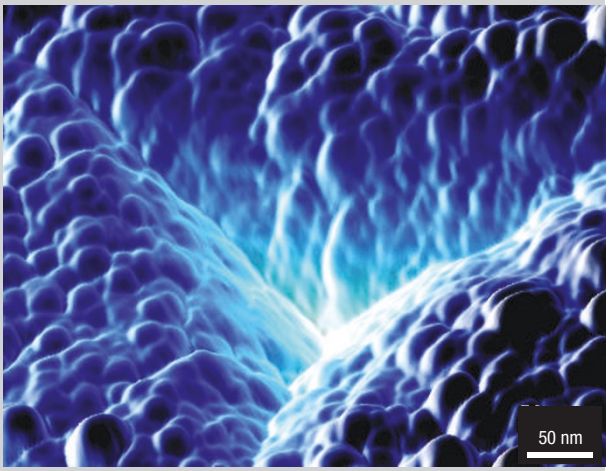
REFERENCES

1. Léger, Y., Besombes, L., Fernández-Rossier, J., Maingault, L. & Mariette, H. *Phys. Rev. Lett.* **97,** 107401 (2006).
2. Tinjod, F., Gilles, B., Moehl, S., Kheng, K. & Mariette, H. *Appl. Phys. Lett.* **82,** 4340–4342 (2003).
3. Grieshaber, W. *et al. Phys. Rev. B* **53,** 4891–4904 (1996).
4. Bracker A. S. *et al. Phys. Rev. Lett.* **94,** 047402 (2005).
5. Vasanelli, A., Ferreira, R. & Bastard, G. *Phys. Rev. Lett.* **89,** 216804 (2002).
6. Wolf, S. A. *et al. Science* **294,** 1488–1495 (2001).
7. Qu, F. & Hawrylak, P. *Phys. Rev. Lett.* **95,** 217206 (2005).
8. Sapra, S., Sarma, D. D., Sanvito, S. & Hill, N. A. *Nano Lett.* **2,** 605–608 (2002).
9. Huang, X., Makmal, A., Chelikowsky, J. R. & Kronik, L. *Phys. Rev. Lett.* **94,** 236801 (2005).
10. Besombes, L. *et al. Phys. Rev. Lett.* **93,** 207403 (2004).

Biomaterials: Close to the bone

Our bones have to be able to withstand many types of impact. Daily activities such as walking, for instance, require a certain amount of elasticity, but the bones in our heels and back are often subject to sudden jolts that compact bone fibrils. Understanding more about the mechanisms that prevent our bones from fracturing under such compressive loads will help in the treatment of problems that result from old age, disease and injury. This is why Christine Ortiz and colleagues at the Massachusetts Institute of Technology are exploring the nanostructural origins of bone strength (*Nano Lett.* doi:10.1021/nl061877k; 2006).

The carbon-based mineralized platelets that coat the collagen fibrils in our bones are known to provide increased strength under tension (pulling). But, how do these minerals affect the elastic response of bone when the fibrils are squeezed together? Ortiz and co-workers wanted to check if the frictional interactions between these minerals helped bones to resist cracks and failure under compression. They combined nanoindentation — which involves pushing a sharp tip into a material — and atomic force microscopy to study how bone responds to compressive forces on sub-10-nm length scales (see image). Their results show that normal bone has a greater resistance to compressive stress than demineralised bone, and that cohesion and friction between the mineralized platelets help them to compress easily, rather than slip. Ortiz's findings are consistent with what is observed in nature: tendons, which respond to tension, contain no minerals, whereas whale bones, which must sustain large compression forces, are almost entirely made of minerals.



AFM image of a nanoindentation in the outer layer of an adult bovine bone.

Jessica Thomas