the carbon nanotube, it would be feasible to 'wrap' it with a well-designed charged molecule. However, it may be difficult to overcome the repulsive van der Waals force of carbon ions and place such a functional molecule as close as 1 Å from the nanotube surface.

The concept behind the molecular dynamics simulations could be tested in large area membranes of carbon nanotubes embedded in a polymer matrix[3,4,7], some of which have exposed tips[7] (Fig. 1b). With these platforms, it is possible to apply the same mechanism that cells use to control chemical transport to large, manmade films. This would have important bulk scale applications in chemical separation, water purification, sensing and drug delivery. Similarly, if the polymer matrix of such modified nanotube membranes is dissolved[8], nanotubes with modified tips could, in principle, be dispersed into solution and subsequently incorporated into cellular micelles to become artificial membrane channels themselves.

A good deal of experimental work remains before the simulations presented by Fang and co-workers can lead to these types of applications. Even so, showing that manmade systems can give selective fluid flow in one direction and at a high rate by controlling the dipole orientation of water is both exciting and intriguing.

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References

1. Joseph, S., Mashl, R. J., Jakobsson, E. & Aluru, N. R. *Nano Lett.* **3,** 1399–1403 (2003).
2. Hummer, G., Rasaiah, J. C. & Noworyta, J. P. *Nature* **414,** 188–190 (2001).
3. Majumder, M., Chopra, N., Andrews, R. & Hinds, B. J. *Nature* **438,** 44 (2005).
4. Holt, J. K. *et al. Science* **312,** 1034–1037 (2006).
5. Quirke, N. & Whitby, M. *Nature Nanotech.* **2,** 87–94 (2007).
6. Gong, X. *et al. Nature Nanotech.* **2,** 709–712 (2007).
7. Kim, S *et al. Nano Lett.* **7,** 2806 –2811 (2007).
8. Chopra, N., Majumder, M. & Hinds, B. J. *Adv. Funct. Mater.* **15,** 858–864 (2005).
9. Hinds, B. J., Chopra, N., Andrews, R., Gavalas, V. & Bachas L. *Science* **303,** 62–65 (2004).

NANOMAGNETISM

Probing magnetism at the nanoscale

Two groups have used scanning tunnelling microscopes to explore the behaviour of magnetic materials in exquisite detail with a view to developing new approaches to data storage.

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The increase in the bit density of magnetic storage devices over recent decades has been more dramatic than that achieved by semiconductor memories, although it is less celebrated. When new magnetic storage media are being developed, two properties are crucial — the magnetic moment and the magnetic anisotropy energy. The first of these is the sum of all the magnetic moments (or spins) in the system, and the second is the energy gained by having the moments point in a certain direction. For small structures, the spins of the constituent atoms all point in the same direction to form a macroscopic moment or 'macrospin'. If the anisotropy energy is large enough, the direction of this macrospin will be sufficiently stable to build a non-volatile memory. However, if the anisotropy energy is not much larger than the thermal energy, the macrospin can reverse direction spontaneously and is said to be superparamagnetic.

It is clear that measuring both the magnetic moment and the magnetic anisotropy with good — ideally atomic — resolution could be very useful. Writing in *Science*, Andreas Heinrich of IBM's Almaden Research Center in San Jose and co-workers report that they have now done exactly this[1]. They have measured the anisotropy energy and spin of individual iron and manganese atoms adsorbed on a copper nitride surface. With a low-temperature scanning tunnelling microscope, they can look at electronic excitations at the iron or manganese site that correspond to a change in the magnetic state of the ions (Fig. 1). By analysing how the energy of these excitations depends on the direction and magnitude of an externally applied magnetic field, they can deduce the probability of the spin pointing in each of five possible directions and determine which direction is most energetically favourable.

It has thus become possible to find out how the magnetic properties of atoms and various test objects — such as metal dimers, trimers and tetramers — depend on their environment. Varying the size and shape of the test objects would give insights into coordination effects; combining different elements would provide new information about magnetic alloys; and varying the distance between the atoms could tell us more about magnetic interactions. Measuring the magnetic moments and anisotropy energies of such simple and well-defined model systems makes comparison with theory straightforward, which will lead to a better theoretical understanding of these systems and increased predictive power.

For a magnetic nanostructure with just one preferred axis of magnetization — known as the 'easy' axis — the macrospin points along (or almost along) this axis for a considerable time, before flipping to point in the opposite direction, again for a considerable time. The amount of time the macrospin points in one direction and the process by which it flips to the other can be measured with a spin-polarized scanning tunnelling microscope (STM)[2] — that is, an STM with a magnetic tip that makes the majority of the spins in the tunnelling current point in the same direction. Now, as Stefan Krause, Roland Wiesendanger and co-workers at the University of Hamburg report in another *Science* paper, it is possible to influence the lifetimes of the two magnetic states by injecting a spin-polarized current[3]. This is not the same as switching the magnetization in the conventional sense because it does not produce a transition from one stable state to another. However, it makes one orientation of the magnetization more likely than the other and therefore comes close to switching.

In most magnetic memory devices, a magnetic field is used to write data, and the giant magnetoresistive effect (for which Albert Fert and Peter Grünberg have just been awarded the Nobel Prize in Physics) is used to read it. However, magnetic random access memories (MRAM) may well take a different approach to writing data in the not too distant future. The cells in an MRAM device consist of two magnetic electrodes separated by a thin

non-magnetic spacer. The magnetization of one electrode is switched by a magnetic field, leading to a change in the resistance of the cell. If the magnetization could be reversed by a current[4–8] rather than a magnetic field, the leads that are currently used to read data could also be used for writing data.

A model system for this approach is to reverse the magnetization of an iron nano-island by driving a spin-polarized current through it from an STM tip. Understanding these reversals of magnetization is therefore central to the development of new memory technologies. However, most experiments are performed on nanopillars or nanowires in which all the action happens in places that are difficult or impossible to probe experimentally. The Hamburg team has now overcome this problem and has been able to explore the relative contributions of the different mechanisms that influence the reversals[3].

First, Krause, Wiesendanger and co-workers measured the lifetimes of the two magnetization states of a nano-island containing about 100 iron atoms on a tungsten surface at temperatures between 48.5 and 50.6 K. From these measurements, performed at a tunnel current of 2 nA, they determined that the anisotropy energy was 133±4 meV. When they increased the tunnel current they found that the lifetimes of both states decreased exponentially, but one decreased faster than the other. This means that one direction for the magnetization becomes more likely as the size of the spin-polarized current through the nano-island is increased. The overall decrease of both lifetimes is attributed to Joule heating raising the local temperature by about 0.5 K. The difference between the lifetimes appears to arise from two effects. One is that the spins in the current induce a net torque on the spins on the nano-island. The other, less important, effect is that the current itself produces a magnetic field (Ampere's Law).

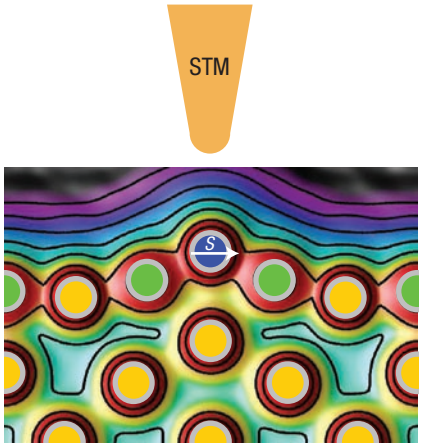

Figure 1 The spin, *S*, on a single magnetic ion, such as iron, has a preferred orientation, which is a necessary condition for single-atom magnetic data storage. In ref. 1, Heinrich and colleagues used a scanning tunnelling microscope (STM) to measure the electronic excitations near an iron atom (blue) adsorbed on a copper nitride surface. These excitations reveal the spin state of the iron atom and how it changes with the direction of an applied magnetic field. Calculations of the electronic density on the surface, such as the one shown here, were instrumental in interpreting the STM results.

Returning to the magnetic properties of single atoms, Heinrich and co-workers determined the anisotropy of Fe along its easy axis (1.55 ± 0.01 meV) and also in the plane perpendicular to the axis (0.31 ± 0.01 meV). However, if the anisotropy had been zero in the plane perpendicular to the easy axis, the iron atoms would prefer to point along a single axis with an anisotropy potentially as high as those reported for cobalt atoms on platinum surfaces[9]. It remains to be seen whether the atomic environments favouring large uniaxial anisotropy that are so desirable for high-density magnetic recording can be created. If they are, the next step will be to combine the approaches of the IBM and Hamburg groups and apply spin-polarized STM to individual magnetic atoms.

References

1. Hirjibehedin, C. F. *et al. Science* **317,** 1199–1203 (2007).
2. Bode, M., Pietzsch, O., Kubetzka, A. & Wiesendanger, R. *Phys. Rev. Lett.* **92,** 067201 (2004).
3. Krause, S., Berbil-Bautista, L., Herzog, G., Bode, M. & Wiesendanger, R. *Science* **317,** 1537–1540 (2007).
4. Slonczewski, J. C. *J. Magn. Magn. Mater.* **159,** L1–L7 (1996).
5. Berger, L. *Phys. Rev. B* **54,** 9353–9358 (1996).
6. Tsoi, M. *et al. Phys. Rev. Lett.* **80,** 4281–4284 (1998).
7. Wegrowe, J. E., Kelly, D., Jaccard, Y., Guittienne, P. & Ansermet, J. P. *Europhys. Lett.* **45,** 626–632 (1999).
8. Myers, E. B., Ralph, D. C. Katine, J. A. Louie, R. N. & Buhrman, R. A. *Science* **285,** 867–870 (1999).
9. Gambardella, P. *et al. Science* **300,** 1130–1133 (2003).

MOLECULAR ELECTRONICS

Ultrafast stop and go

Theoretical physicists have predicted that ultrashort laser pulses can be used to drive electrical currents through single molecules, and also to stop currents in molecular junctions.

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Finding ways to generate electrical currents with light is a problem of great practical importance and has occupied the minds of scientists for more than a century. Much of this research has focused on understanding photosynthesis or making solar cells more efficient, but the potential to control fast circuits optically will also require an understanding of the fundamental limits for transferring light to electrical energy. In particular, downscaling in nanoelectronics has reached the level at which a single molecule controls the operation of a device. For these systems, the quantum mechanical nature of electrons becomes important, and it may be possible to observe novel effects when they interact with light.

Writing in *Physical Review Letters*, Ignacio Franco and Paul Brumer of the University of Toronto in Canada and Moshe Shapiro of the Weizmann Institute in Israel[1] propose how to drive an ultrafast current in a single molecule with a laser pulse. Conversely, in *Europhysics Letters*, Guan-Qi Li and Ulrich Kleinekathöfer from Jacobs University and Michael Schreiber of the Technical University Chemnitz, both in Germany[2], predict what appears to be the opposite effect: they demonstrate that a laser pulse impinging on a molecular junction can interrupt a steady current, giving rise to a gap in an otherwise regular train of electrons. What is notable about both of these studies is that light assumes the role