metallic) and the degree to which a parallel alignment of the nanotubes within the array is achieved (±17°).

Perhaps the most astonishing feature of this approach is the enormous nanotube density that can be obtained: the distance between adjacent nanotubes within the arrays is less than 5 Å and is apparently limited only by the van der Waals separation of the nanotubes (Fig. 1b). This nanotube density leads to very large current densities. For example, when the transistors have a gate length of 3 μm, which is larger than the average nanotube length, the width-normalized drive currents are as large as 4 μA μm^{-1}.

This current density may not seem that impressive when compared with low-temperature polycrystalline silicon thin-film transistors (TFTs), which are commonly used in active-matrix organic light-emitting diode displays and typically have drive currents of 50 μA μm^{-1} when using similar gate lengths[9]. Or when compared with polycrystalline metal oxide TFTs, which are beginning to replace hydrogenated amorphous silicon TFTs in advanced active-matrix liquid-crystal displays and can have drive currents of 5 μA μm^{-1} for a gate length of 20 μm (ref. 10). However, it is important to note that when the gate length of a nanotube transistor exceeds the average nanotube length, the drive current is limited by the relatively inefficient charge transfer between the tubes.

A more revealing analysis is then perhaps to look at transistors in which the gate length is shorter than the average nanotube length. And indeed, for transistors with a gate length of 120 nm, Cao and colleagues have measured impressive drive currents of 100 μA μm^{-1}. This is within a factor of ten of the drive currents of state-of-the-art silicon metal–oxide–semiconductor field-effect transistors at the 22-nm technology node[11,12], despite the lack of contact doping in the nanotube transistors. Furthermore, respectable on/off current ratios of around 100 can be maintained in these devices when they are devoid of metallic impurities and composed exclusively of semiconducting nanotubes.

The encouraging performance of these devices invites the question — will carbon nanotubes ever replace silicon in microprocessors and memory? When posed to experts in industry, this question is typically met with responses that range from fervour ('absolutely') to a chuckle ('never'). The truth is that although the end of silicon has been predicted to be imminent for years, silicon (shaped as fins or wires) is on track to meet the roadmap targets for the 14-nm and 10-nm nodes. But keeping up this pace has already led to the introduction of numerous exotic materials around the silicon channel (SiGe/SiC stressors, HfSiON/La$_2$O$_3$ gate dielectrics, TiN gates, NiSi/Cu contacts, SiBCN spacers). So beyond the 7-nm node, when the lithographic burdens will become almost unbearable, merely replacing those last few silicon atoms in the channel with carbon (whether in the form of tubes or ribbons) might actually be the least of Intel's and Samsung's worries. ❐

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MOLECULAR SPINTRONICS

Stretch for a moment

The spin of a single-molecule magnet is coupled to the vibrational motion of a single carbon nanotube.

Richard E. P. Winpenny

One of the aims of molecular electronics is to realize devices that make use of the quantum mechanical properties of a single molecule. The challenges are enormous however. For example, it is very difficult to control the location of a tiny object like a molecule. Also, it is necessary to design experiments that permit the reliable study of the physics of single molecules. Finally, and most importantly perhaps, the physics of a single molecule has to be linked to the design of devices intended for the macroscopic world.

Now writing in *Nature Nanotechnology*[1], Wernsdorfer and co-workers report on their experiment that links the magnetic spin of a single molecule with the vibrational modes of a carbon nanotube (CNT). Carbon nanotubes are already used as components of nanoelectromechanical systems due to their very high Young's modulus, which gives them a remarkable stiffness for such a light element as carbon. The combination of stiffness and lightness has led to their use in ultrasensitive devices for ultrasensitive mass sensing[2–4], and for measuring magnetic behaviour of nano-objects[5]. Wernsdorfer and co-workers use a terbium single-molecule magnet (SMM) as the spin centre, and show that transport through the CNT is influenced by switching the spins of the terbium SMM firmly bound to it (Fig. 1a).

The terbium SMM is a derivative of the complex bis(phthalocyaninato)terbium(III) (TbPc$_2$) (ref. 6). Functionalization introduces a pyrene group that binds strongly to the surface of the CNT. The magnetic behaviour of TbPc$_2$ is due to a very well isolated doublet defined by the total angular momentum $J = 6$ with $J_z = \pm 6$. Terbium has a nuclear spin $I = 3/2$ and hence each state of the ground state doublet is split into four states. In high magnetic fields, the TbPc$_2$ can only lose magnetization through a direct quantum tunnelling process $|J_z, I_z\rangle \rightarrow |-J_z, I_z\rangle$. As there are four possible values for I_z (+3/2, +1/2, −1/2, −3/2) there should be four such magnetization losses possible, separated by energy gaps due to the nuclear magnetic moment (Fig. 1b). Previously, this has been used to measure the nuclear spin of terbium directly by transport measurements through TbPc$_2$ (ref. 7).

In the experiment by Wernsdorfer and colleagues[1] the transport through a CNT shows four jumps in the differential conductance at specific external fields (Fig. 1c), corresponding to the nuclear spin states of the terbium. However, for these variations in conductance to occur, the nuclear spin of the terbium has to be somehow coupled to the nanotube. This is

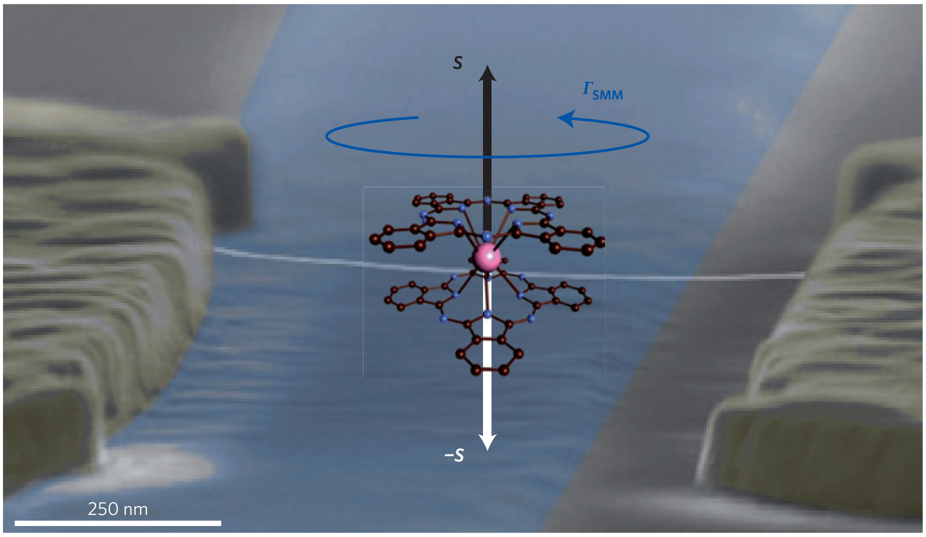

Figure 1 | The CNT–SMM device. The spin of the SMM from *S* (black arrow) to –*S* (white arrow) in an external magnetic field induces a rotation of the SMM (Γ_{SMM}, blue arrow) under conservation of the total angular momentum, which induces a stretch in the CNT (white thread). The SMM is shown as a chemical structure that is overlaid on a false-coloured scanning electron microscope image of a CNT suspended between two contacts[1]. Terbium, pink; nitrogen, blue; carbon, black.

possible through coupling of the electron spin with the longitudinal stretching mode of the CNT, hence, in quantum mechanical terms, the longitudinal phonons. The origin of the coupling stems from the conservation of total angular momentum — if the magnetic spin of terbium reverses (rotates) it must cause a rotation of the entire terbium molecule (Fig. 1a). This molecule is firmly grafted to the surface of the CNT, so that it causes the CNT to stretch. We could imagine attempting to turn a stamp firmly fixed to an envelope; rotating the stamp causes a distortion of the supporting paper.

The estimated magnitude of the coupling between the spin of the SMM and the vibrational phonon is sufficiently large to account for the observations. It may also account for the lack of quantum tunnelling of magnetization of the SMM in this device, although the authors correctly note that further experiments are needed to prove such a claim.

It is hard to predict the practical implications of these results. This group has previously reported single-molecule transistors[7] and molecular spin valves[8]. One danger in discussing such groundbreaking science is that we can only imagine creating nanodevices that have equivalents in the macroscopic or mesoscopic world. It is an inevitable part of human behaviour that we seek analogues when we try to understand new physics. Perhaps sometimes this need to use existing devices as analogues limits us from seeing the possibilities of entirely new types of device at the nanoscale. Wernsdorfer and co-workers couple the magnetic spin with vibrational motion; there are macroscopic devices that couple magnetism and motion — the magnetic stirrers beloved of all chemists are a classical example. But these are clearly very different types of device. Perhaps it is through coupling of the many different types of quantum level of a molecule — nuclear spin, electron spin, stretching, rotations — that new types of device and logic can be created. Such devices would have no classical counterpart, and that could lead to entirely new technology. ❐

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SKYRMIONS

Moving with the current

Numerical simulations suggest that disorder and damping have little effect on the current-induced motion of nanoscale magnetic whirls known as skyrmions.

Achim Rosch

Modern electronics is principally based on the manipulation of the charge of the electron. However, the magnetic moment of the electron — the spin — can also be used to create devices with novel functionalities and potentially superior performance, such as new types of memory[1] or devices with low power consumption. To develop these spin transport-based devices, new ways are sought to manipulate magnetic structures with electric currents. Recently, it has been shown experimentally[2] that nanoscale magnetic whirls, known as skyrmions[3,4], can be manipulated with electric current densities that are more than 100,000 times smaller than those used to move other magnetic textures like the interface between magnetic domains (domain walls)[1]. Writing in *Nature Communications*, Naoto Nagaosa and colleagues[5] at the University of Tokyo and the RIKEN-ASI in Japan have now shown that the reason why only small electric currents are required to induce