Most theorists' favourite microscopic lattice models of strongly correlated electrons (Hubbard, t-J and so on) are usually written in terms of the original 'bare' electrons, in contrast to effective actions like that of Kaul *et al.*[1], constructed from holon and spinon degrees of freedom. Interestingly, Kaul *et al.* offer simple predictions that can be tested by numerical simulations of microscopic models of correlated electrons[4]. It would indeed be of great interest to know whether these lattice models can, by themselves, exhibit such a rich phase diagram. On the experimental side, ongoing effort in sample preparation and signal resolution will steadily reinforce the constraints on theories of strongly correlated electrons, subjecting the ideas put forward by Kaul *et al.* to more rigorous tests.

References

1. Kaul, R. K., Kim, Y. B., Sachdev, S. & Senthil, T. *Nature Phys.* **4,** 28–31 (2008).
2. Kanigel, A. *et al. Nature Phys.* **2,** 447–451 (2006).
3. Anderson, P. W. *Science* **235,** 1196–1198 (1987).
4. Dagotto, E. *Rev. Mod. Phys.* **66,** 763–840 (1994).
5. Doiron-Leyraud, N. *et al. Nature* **447,** 565–568 (2007).
6. LeBoeuf, D. *et al. Nature* **450,** 533–536 (2007).

MAGNETIC TUNNEL JUNCTIONS

Spin-torque measured up

The 'spin-transfer torque effect' could provide a powerful means of controlling the orientation of spins with electric currents rather than magnetic fields in future spintronic devices. Quantitative measurements of this effect represent an important next step.

Maxim Tsoi

is in the Department of Physics, University of Texas at Austin, 1 University Station, C1600, Austin, Texas 78712-0264, USA.

e-mail: tsoi@physics.utexas.edu

As conventional electronic circuits shrink to smaller and smaller dimensions, not only do they become more difficult to build, but require more power to run, which in turn generates more heat that must be dissipated to avoid damage. This represents a serious challenge to continuing the rate of improvement in computer power and cost that has been maintained over the past forty years, and which is responsible for much of the economic prosperity seen over this period. Spintronics, in which information is encoded in electronic spin rather than electronic charge, is one technology that could enable us to exceed the limitations faced by the electronics industry. Reorienting an electron's spin is in principle faster to implement and requires less power than moving it from one place to another. As well as offering a potentially faster and more energy efficient means of processing information than conventional electronics, the use of spin could enable qualitatively different sorts of functions to be performed, such as quantum computing. But for this to be realized, ways of manipulating spin that do not rely on magnetic fields, the generation of which is usually energy inefficient, must be developed. One promising approach exploits the so-called spin-transfer torque effect[1,2], in which the distribution of spins in a magnetic material is influenced by a spin-polarized electrical current. But although the occurrence of this effect has been unambiguously identified, its precise details have remained unclear. Two studies in this issue — one on page 67 by Sankey and colleagues[3], and the other on page 37 by Kubota and colleagues[4] — describe the first quantitative measurements of both the magnitude and direction of the spin-transfer torque in a magnetic tunnel junction.

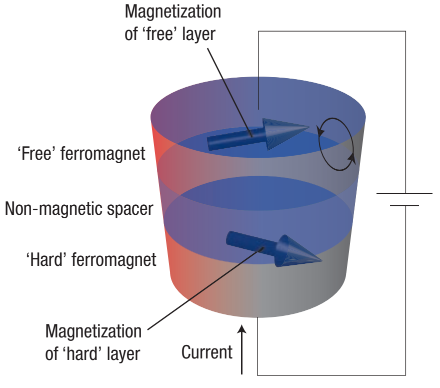

Figure 1 Excitation of a ferromagnet by spin-transfer torque. The passage of a current through a 'hard' magnetic layer causes it to become spin-polarized. When this current is subsequently injected across a thin non-magnetic spacer layer and into a 'free' magnetic layer, the realignment of its polarization induces a torque on the magnetic moment of the free layer, causing it to precess and even reverse.

When an unpolarized current passes through a magnetized ferromagnetic material, it becomes spin-polarized in the direction of the materials' magnetization. Similarly, when a spin-polarized current is injected into a ferromagnetic material whose magnetization direction is different, it will cause the polarization of injected current to change. The resulting rotation of the injected current generates a torque on the magnet — a spin-transfer torque — which in turn can cause its magnetization to precess and potentially even reverse direction completely[1,2]. This process typically takes place in a nanometre-sized pillar composed of two ferromagnetic layers separated by a non-magnetic layer (see Fig. 1). The first layer is usually a hard magnetic layer whose magnetization is resistant to change, which serves to spin-polarize any current that passes along the pillar. And the second layer, also known as the 'free' layer, is one that is more susceptible to the torque generated by an injected current. The ability to change the magnetization of this free layer with an electric current has obvious implications for improving the speed and reducing the size of magnetic random access memories (MRAMs). Another possible application is based on the spin-transfer-induced precession of magnetization, which converts a d.c. current input into an a.c. voltage output. The frequency of such a precession can be tuned from a few GHz to over 100 GHz by changing the applied magnetic field and/or the d.c. current, effectively resulting in a current-controlled oscillator to be used in practical microwave circuits.

The initial observations of spin-transfer torque were made in all-metal systems[5–9] — that is, with two ferromagnetic metal layers separated by a non-magnetic metal. Recently, the phenomenon has also been demonstrated in magnetic tunnel junctions[10,11] (MTJs), in which the layer separating the two ferromagnetic layers is a thin insulator rather than a non-magnetic metal. In such a structure, when the magnetizations of the two ferromagnetic layers are parallel, the probability that electrons with similarly polarized spins will tunnel between them is high, and so its resistance to the flow of current is low. In contrast, when the magnetizations are antiparallel, the tunnelling probability is low and the resistance is high. The ability to distinguish the relative polarization of the two layers from their electrical resistance is one of the things that makes them attractive candidates for the basic building block of a magnetic random access memory, whose simple cross-point architecture and non-volatile character considerably reduce the power consumption and increase the storage density. The free layer of such a structure could in principle be switched magnetically between the high and low resistance states ('1' and '0' memory states), in the same way as the bits of a magnetic hard disk are switched. But doing so without affecting the magnetization of the underlying hard layer or those of neighbouring devices is a challenging task, and one that limits the miniaturization and ultimate storage density that could be achieved. Thankfully, the spin-transfer torque effect provides an electrically driven alternative. What has been missing has been accurate information about the details of this process, a shortcoming that the two present studies address[3,4].

In the first study, Sankey and colleagues use a technique known as spin-transfer-driven ferromagnetic resonance (ST-FMR) to measure the bias- and angular-dependence of the spin-transfer torque in MgO-based MTJs. In this technique the free magnetic moment of an MTJ is driven into resonance not by a microwave-frequency magnetic field, as occurs in conventional FMR, but by an electric current modulated at a microwave frequency. As this resonant dynamics is driven by the spin-transfer torque induced by the current bias, analysis of the ST-FMR signal enables the collection of detailed information on the magnitude and direction of this torque. At low currents, the authors find that the torque lies in the plane defined by the hard and free magnetizations of MTJ, and its magnitude is in excellent agreement with a prediction for highly spin-polarized tunnelling. With increasing bias, this in-plane component remains large, which is quite unexpected in light of the decrease in tunnelling magnetoresistance that is observed. The authors also find that the torque vector rotates out of the plane, which may efficiently assist magnetic reversal in practical devices.

In the second study, Kubota and colleagues take a similar approach but exploit the so-called spin-torque diode effect to access quantitative information about the spin-transfer torque in MgO-based MTJs. This enables them to go a step further and extend the range of bias currents to the value where the spin-transfer torque actually switches the free magnetic moment of an MTJ. Similar to Sankey *et al.,* Kubota and colleagues find that the in-plane torque vector agrees well with predictions, and detect a considerable perpendicular component at higher biases. But, surprisingly, they find very different values for the in-plane torques necessary to promote the switching at positive and negative biases. The latter may indeed indicate the importance of the torque's perpendicular component for magnetic reversal.

The quantitative information on spin torque obtained by both groups[3,4] has major implications for the use of nanoscale spin-transfer devices. First, they confirm the high efficiency of spin-transfer torque in MTJ-based magnetic memory operated at high biases. However, the threshold bias for magnetic switching is still too high for integration with existing electronic technology and too destructive for long-term operation using existing MTJ materials and structures. On this score, the results suggest that only marginal improvements in spin-transfer-torque efficiency will be possible, even if 100% tunnelling spin-polarization were achieved. But they also suggest that the path to improving the other characteristics of MTJs for spin-torque applications could be achieved through optimizing other material properties such as magnetic anisotropy and damping. Whether this is the correct path to practical spintronic devices only time will tell.

References

1. Slonczewski, J. C. *J. Magn. Magn. Mater.* **159,** L1–L7 (1996).
2. Berger, L. *Phys. Rev. B* **54,** 9353–9358 (1996).
3. Sankey J. C. *et al. Nature Phys.* **4,** 67–71 (2008).
4. Kubota, H. *et al. Nature Phys.* **4,** 37–41 (2008).
5. Tsoi, M. *et al. Phys. Rev. Lett.* **80,** 4281–4284 (1998).
6. Myers, E. B., Ralph, D. C., Katine, J. A., Louie, R. N. & Buhrman, R. A. *Science* **285,** 867–870 (1999).
7. Sun, J. Z. *J. Magn. Magn. Mater.* **202,** 157–162 (1999).
8. Wegrowe, J.-E., Kelly, D., Jaccard, Y., Guittienne, P. & Ansermet, J.-P. *Europhys. Lett.* **45,** 626–632 (1999).
9. Tsoi, M. *et al. Nature* **406,** 46–48 (2000).
10. Huai, Y., Albert, F., Nguyen, P., Pakala, M. & Valet, T. *Appl. Phys. Lett.* **84,** 3118–3120 (2004).
11. Fuchs, G. D. *et al. Appl. Phys. Lett.* **85,** 1205–1207 (2004).

ERRATUM

How to build a critical mind

JOHN M. BEGGS

Nature Physics **3,** 834–835 (2007)

In this News & Views article, the second author name given in reference 6 was incorrect. The correct full reference is Levina, A., Herrmann, J. M. & Geisel, T. *Nature Phys.* **3,** 857–860 (2007).