SPINTRONICS

Field-free ringing of nanomagnets

That the magnetic orientation of ferromagnets can be changed using magnetic fields has been known for centuries. But the exploration of magnetization control without any additional magnetic field has only just begun.

Thomas J. Silva

is in the Electromagnetics Division, National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA.
e-mail: silva@boulder.nist.gov

Ever since William Gilbert's sixteenth century treatise *De Magnete*, it has been known that magnetic fields can be used to manipulate the magnetic orientation of ferromagnets. This has been the foundation for electronic applications of magnetic materials for the past 100 years, in the form of, for example, inductors, microwave isolators and magnetic disk drives. But in 1996, our understanding of how magnetization can be controlled was fundamentally altered when John Slonczewski[1] and Luc Berger[2] independently predicted that spin-polarized current in a magnetic conductor can affect its magnetization, due to a purely quantum-mechanical transfer of angular momentum from the charge carriers to the magnetization. To observe this effect, however, current densities on the order of 10^8 amperes per square centimetre are required to generate sufficient torque to overcome the intrinsic viscous damping (the magnetic analogue of mechanical friction). It was not until the electron-transport properties of nanometre-sized conducting magnetic heterostructures could be studied that there was a chance of seeing such a phenomenon. The first experimental confirmations[3,4] of the theories of Slonczewski and Berger appeared in 1998–1999, and the effect — alternately known in the literature as 'spin torque' or 'spin transfer' — has been the subject of feverish investigation ever since. Now two works in this issue, by Pribiag and colleagues[5] (page 498) and by Boulle and colleagues[6] (page 492), show promising approaches whereby spin torque may find its way into commercial applications.

Spin torque can be used both to switch magnetic orientation[3] and to cause the magnetization to ring at microwave frequencies[7]. The latter heralds the emergence of a spin-based analogue to the voltage-controlled oscillator, and holds great promise

William Gilbert (1544–1603). Magnetic fields have been the primary means to control magnetization since 1600, when Gilbert published his observation that the magnetic fields from lodestone (magnetite) could be used to orient the magnetization in an iron needle. Now, 400 years on, we are learning how to control magnetization using the quantum-mechanical spin of electrons, without any additional magnetic field.

for enhanced performance in mobile phones and microchips, where the limited bandwidth of the interconnects between components is starting to constrain device performance. Whereas spin-torque switching can occur in the absence of any applied magnetic field, experiments to study microwave generation via spin torque have so far required application of large magnetic fields of the order of 2,000 times that of the Earth, as only in the presence of sufficient magnetic field does the magnetic potential-energy landscape have a single minimum. Most magnetic materials have at least two intrinsic energy minima due to anisotropy of the material's crystal structure or physical shape. With a single minimum, the magnetization has no choice but to oscillate in response to the destabilizing spin torque. The requirement for large magnetic fields has stymied the implementation of spin-torque oscillators as practical nanoscale microwave sources; the advantages of having a microwave emitter

that is only a few hundred nanometres in dimension are greatly outweighed by the need to incorporate, cumbersomely, a large source of static magnetic field.

Pribiag *et al.*[5] and Boulle *et al.*[6] show that it is possible to generate microwave signals in spin-torque nano-oscillators (STNOs) without applying any magnetic field. Their developments — which complement recent results that demonstrated the emission of relatively large and narrowband radiofrequency signals of several hundred megahertz from STNOs in zero applied field[8] — are an important step to secure spin torque a niche in the nascent field of spintronics[9], a field that has already yielded astonishing improvements in performance of hard disk drives and magnetic random access memory. The two new works[5,6] show that zero-field signal emissions can be pushed into the gigahertz regime, and that the entire device can be confined to a nanopillar geometry that is only several hundred nanometres in size.

The two groups[5,6] used very different approaches to eliminate the necessity for a strong magnetic field. Pribiag and colleagues[5] fabricated an STNO where one of the two magnetic layers was sufficiently thick — 60 nanometres — as to form a magnetic vortex structure in the absence of any applied magnetic field. The magnetic vortex has a circulating magnetic orientation that wraps around a topological singularity, or 'core', at the centre of the vortex structure. Unlike the case of the uniformly magnetized state, such a vortex structure has a single energy minimum, thereby avoiding the large field requirement altogether. By comparing their data with finite-element micromagnetic simulations, they show that the low-field oscillations they observe are the result of gyromagnetic precessional oscillations in the vortex core. Vortex core dynamics in an external applied microwave field have been observed before[10], and a particular signature of vortex core motion is that the frequency is a very weak function of applied magnetic field. Indeed, Pribiag *et al.* see that the microwave emission from their device has a barely discernable dependence

on applied field, in strong support of their hypothesis of vortex core dynamics. The results are somewhat surprising, because it is usually assumed that a thick magnetic layer in a spin-torque device has too much intrinsic damping to be excited. However, the micromagnetic simulations clearly show that the surface torque due to spin transfer is sufficiently large to drive vortex core dynamics at the interface where the spin transfer occurs.

Boulle and co-workers[6] use devices with two different magnetic materials in the multilayer structure: a nickel–iron alloy know as Permalloy, and cobalt. They find that such a device generates microwave signals even when driven with current in weak or even absent magnetic fields. To understand how the use of these two materials can cause zero-field magnetic oscillations of the Permalloy layer requires some understanding of the more esoteric details of diffusive spin transport in magnetic multilayers. Suffice it to say that the intrinsic spin-transport

properties are sufficiently different for these two ferromagnetic materials that the sign of the spin torque that gives rise to the oscillations can change when the relative magnetization angle between the two layers is sufficiently large. Such a sign change effectively prevents the magnetization from falling into any energy minima that may exist. Similar to what Pribiag et al.[5] saw, the frequency of the microwave emissions could be controlled by changing the direct current. However, in contrast to results of Pribiag et al. the device of Boulle et al.[6] exhibits a rather significant dependence of output frequency on applied magnetic field — strong evidence that the zero-field oscillations are not the result of an unexpected vortex structure in the Permalloy–cobalt nanopillar structure.

By showing that microwave emissions from STNOs are not dependent on large external magnetic fields, a major impediment to the practical application of these novel nanoscale devices has been removed. However, several technological

hurdles remain to be overcome, not the least of which is the relative weak output power of the order of picowatts. To tackle the power problem, several avenues seem promising, including the incorporation of giant tunnelling magnetoresistance into STNOs, the development of phase-coherent arrays of STNOs, or some combination of these two approaches. Once the power problem is solved, STNOs may very well usher in a new era where spintronics makes the first steps out of data storage and into mainstream electronic applications.

References
1. Slonczewski, J. C. *J. Magn. Magn. Mat.* **159,** L1–L7 (1996).
2. Berger, L. *Phys. Rev. B* **54,** 9353–9358 (1996).
3. Myers, E. B., Ralph, D. C., Katine, J. A., Louie, R. N. & Buhrman, R. A. *Science* **285,** 867–870 (1999).
4. Tsoi, M. *et al. Phys. Rev. Lett.* **80,** 4281–4284 (1998).
5. Pribiag, V. S. *et al. Nature Phys.* **3,** 498–503 (2007).
6. Boulle, O. *et al. Nature Phys.* **3,** 492–497 (2007).
7. Kiselev, S. I. *et al. Nature* **425,** 380–383 (2003).
8. Pufall, M. R., Rippard, W. H., Schneider, M. L. & Russek, S. E. *Phys. Rev. B* **75,** 140404 (2007).
9. Wolf, S. A. *et al. Science* **294,** 1488–1495 (2001).
10. Guslienko, K. Y. *et al. J. Appl. Phys.* **91,** 8037–8039 (2002).

SUPERGRAVITY

Finite after all?

Advances in theoretical computation raise again the possibility that 'maximal supergravity' might be free of the ultraviolet divergences that have plagued quantum gravity theories — with puzzling implications for string theory.

Kellogg Stelle

is in the Theoretical Physics Group, Imperial College London, London SW7 2AZ, UK.

e-mail: k.stelle@imperial.ac.uk

The basic problem in formulating a quantum theory of gravity was already recognized in the earliest approaches to the problem back in the 1930s: the dimensional character of Newton's constant gives rise to ultraviolet-divergent quantum-correction integrals. Ultraviolet divergences can arise because the energies of virtual objects contributing to quantum corrections extend up to infinity. In the 1970s, the problem was confirmed explicitly in the first Feynman-diagram calculations of the radiative corrections to systems containing gravity as well as matter[1]. The time lag between the general perception of the UV-divergence problem and its first concrete demonstration occurred because of the complexity of Feynman-diagram calculations involving gravity. The necessary techniques grew out of the long

struggle to control, in a Lorentz-covariant manner, the quantization of non-abelian Yang–Mills theories, which became the basis of the standard model of weak and electromagnetic interactions and of quantum chromodynamics.

With the advent of supergravity[2,3] in the mid-1970s, hopes rose that the specific combinations of quantum fields in supergravity theories might tame the gravitational UV-divergence problem. Indeed, it turns out that all irreducible supergravity theories in four-dimensional spacetime — that is, theories in which all fields are irreducibly linked to gravity by supersymmetry transformations — have remarkable cancellations in Feynman diagrams with one or two internal loops.

There is a sequence of such irreducible (or 'pure') supergravity models, characterized by the number N of local (that is, spacetime-dependent) spinor parameters. In four-dimensional spacetime, minimal, or $N = 1$, supergravity thus has four supersymmetries corresponding

to the components of a Majorana (or 'real') spinor transformation parameter. It turns out that the maximal possible supergravity[4] in four-dimensional spacetime has $N = 8$ spinor parameters, hence 32 independent supersymmetries.

The hopes for 'miraculous' UV-divergence cancellations in supergravity were subsequently dampened by the realization that the divergence-killing powers of supersymmetry most likely do not extend beyond the two-loop order for generic pure supergravity theories. Moreover, the flowering of superstring theory in the 1980s and 1990s — in which the UV-divergence problems of gravity are cured by a completely different mechanism replacing the basic field-theory point-particle states by extended relativistic object states — pushed the UV-divergence properties of supergravity out of the limelight.

Nonetheless, among some researchers a faint hope persisted that at least the maximal $N = 8$ supergravity might have special UV properties. This hope was bolstered by