possess the quality of non-volatility, something extremely important in a world where computers are increasingly carried and worn. The trouble with devices operated by classical magnetic fields is that they need more power as they become smaller. Spin transfer reverses this trend because the effect becomes naturally stronger on decreasing the size of the device. The direct electrical control of magnetism therefore promises high-performing devices with relatively low power needs, which could dominate the scene for many years to come.

Will we then see vortex-core memories in our computers or mobile phones soon? It is probably too early to know. The concept is certainly worth considering. The vortex core is one of the smallest, most robust objects we possess in nanotechnology, and the possibility of switching between its two bistable states with an electrical current certainly improves the prospects of integrating magnetic materials in electrical circuits with no clash with scalability, and in the world of new device technologies scalability is king. The problem is that the core cannot be detached from the rest of the vortex. And the vortex state can only exist in intermediate-size devices, transforming into a single domain state if the size of the disk is reduced too much. Perhaps there are other applications, especially given the intense magnetic field gradients that exist in the vicinity of the core. Such gradients might find use in biotechnology where they could be used to trap a biologically functionalized magnetic bead. Regardless of the end use, the paper by Ono and colleagues is an important step in expanding our options of how to configure electricity and magnetism to make the best possible hybrid devices.

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DATA STORAGE

Multiferroic memories

Multiferroics might hold the future for the ultimate memory device. The demonstration of a four-state resistive memory element in a tunnel junction with multiferroic barriers represents a major step in this direction.

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Multiferroic materials simultaneously show ferromagnetism and ferroelectricity. They hold great potential for applications as the multiferroic coupling allows switching of the ferroelectric state with a magnetic field and vice versa. Significantly, multiferroics could lead to a new generation of memory devices that can be electrically written and magnetically read. On page 296 of this issue, Martin Gajek and co-workers report a significant breakthrough in the quest for the ultimate memory device[1]. The authors demonstrate that thin films of lanthanum bismuth manganite (LBMO) remain ferromagnetic and ferroelectric down to thicknesses of 2 nm and, when used as a multiferroic tunnelling junction, act as a four-state resistive system. Their spin-filter device is a subtle complement to related work on more conventional magnetic tunnel junctions (Fig. 1), and the ferroelectric behaviour in such ultrathin films is an achievement in itself.

Recently, ferroelectric random access memories (FeRAMs) have achieved fast access speeds (5 ns), high densities (64 Mb) and embodiments in several different materials (lead zirconate titanate, strontium bismuth tantalate and bismuth ferrite), but they are limited by the need for a destructive read and reset operation. By comparison, magnetic random access memories (MRAMs), have been lagging far behind, although Freescale Corporation reported commercial production in 2006 of a smaller MRAM for testing.

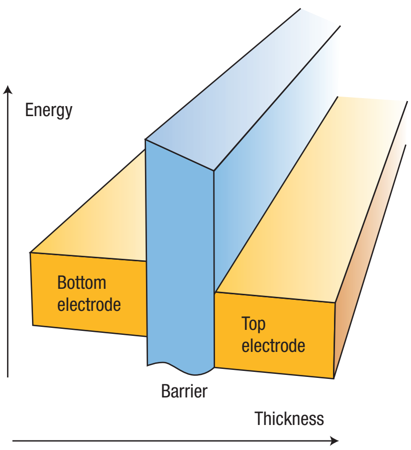

Figure 1 Schematic of a tunnel junction. Electrons tunnel from the bottom electrode through the barrier into the top electrode.

The appeal of multiferroics is that they offer the possibility of combining the best qualities of FeRAMs and MRAMs: fast low-power electrical write operation, and non-destructive magnetic read operation. At the 256 Mbit level, such memory devices, in the words of Clayton M. Christensen[2], would be a "disruptive technology" and could eliminate competition such as EEPROMs (electrically erasable programmable read-only memories) for applications including megapixel photo memories for digital cameras or audio memories in devices such as mp3 players.

Multiferroic magnetoelectric materials were studied extensively by Hans Schmid in Geneva from 1970 to 1990 (ref. 3) with nickel iodine boracite as the paradigm material. A primary aim was to provide a memory element that had more than the two states used by Boolean algebra. A four-state logic (Fig. 2), or even better, octal logic, would permit an exponentially increased computing capacity. Unfortunately the boracites function only at very low temperatures and generally grow in needle-form. Their study was never extended to thin films and was never commercialized.

In the present work, Gajek *et al.* exploit the large tunnel magnetoresistance in junctions (Fig. 2) that have a ferromagnetic electrode. Notably, there is also an electroresistance effect influenced by the electric polarization *P* in the LBMO barrier. The combination of these two effects — magnetoresistance plus electroresistance — yields a four-state resistive memory element.

Several other groups have recently emphasized the study of ferroelectric films as resistive memory elements rather than capacitors. Capacitors store information as +*P* or –*P* polarization, which can be read by an applied voltage. Resistive memories, on the other hand, can be read more simply, for example, by monitoring the source–drain current in a field-effect transistor. Notable in this area has been the work in Aachen-Juelich[4], as well as earlier work by Bednorz and co-workers[5]. However, polarization-dependence of resistance does not only arise from tunnelling mechanisms, and more pedestrian effects are often dominant[6,7]. Therefore, clear experiments on tunnelling through multiferroic barrier materials are particularly welcome. The present study by Gajek *et al.* seems unambiguous and has a sufficient signal-to-noise ratio for a real memory system. The slight electrical hysteresis in these tunnel junctions can in general be an artefact of the electromigration of ions (creep)[8] rather than true polarization reversal, but this has been examined separately by the present authors[9].

In order to make a multiple-state magnetoelectric memory, one must be able to access the four states formed by electric polarization *P* and magnetization *M* (Fig. 1): (+*P*,+*M*), (+*P*,–*M*), (–*P*,+*M*), and (–*P*,–*M*). However, this is not just a matter of symmetry, but also of multiferroic coupling. If we wish to switch from (+*P*,+*M*) to (+*P*,–*M*) by applying an electric field, a significant *P*–*M* coupling is required. Unfortunately this implies that the four states are not truly independent[10]. In the extreme limit in which the polarization and magnetization are fully coupled (as is likely in $BaMnF_4$, see ref. 11), only the states (+*P*,+*M*) and (–*P*,–*M*) — or only (+*P*,–*M*) and (–*P*,+*M*) — are accessible and this is, of course, not a four-state memory. Therefore, the kind of polarization–magnetization correlation studied by Gajek and co-workers is an important new topic.

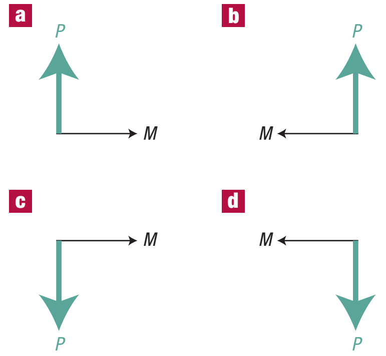

Figure 2 The four degrees of multiferroic order. **a**–**d**, Electric polarization *P* and magnetization *M* can assume four non-collinear states in a multiferroic crystal. In this schematic with arbitrary magnitudes, the directions are in real space. For some materials the spins and polarizations are highly correlated[10,11], so that only pairs **a** and **d** or alternatively **b** and **c** are readily accessible.

From a practical point of view, the effects reported by Gajek *et al.* occur at a 2 V bias operation, compatible with the standard silicon-chip 5 V-logic level. However, the device analysed would require liquid nitrogen cooling and the search for a room-temperature ferroelectric ferromagnetic remains, although reports suggest that $K_3F_5Fe_{15}$ or $A_3(MF_6)_2$ (A = Sr, Pb; and M = Ti, V, Cr, Fe) may satisfy this need[12]. It is clear that significant practical obstacles such as these need to be overcome before multiferroic tunnelling junctions can be commercialized. Nevertheless, the work by Martin Gajek and colleagues represents a major advance towards the ultimate memory and it will be exciting to follow further developments in this field.

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NANOCOMPOSITES

Model interfaces

To achieve the often-promised capabilities of polymer nanocomposites, the properties of the interfacial region between polymer and filler must be controlled. Model nanocomposites offer a path towards understanding the physics of this region.

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Nanoscale fillers in polymers offer the promise of multifunctional polymer composites with enhanced mechanical, electrical, optical, thermal or magnetic properties without a loss in transparency. Developing nanocomposites for advanced technological applications, however, requires the ability to tailor the properties. A major challenge in achieving the ability to control and predict nanocomposite properties is a quantitative understanding of the structure and properties of the interfacial polymer at the boundary with the filler particles. In nanocomposites this interfacial polymer constitutes a significant volume fraction of the composite even at low filler concentrations (see Fig. 1), and has been shown to have properties different from the bulk[1]. Few models address this interfacial region, and there has been limited experimental measurement of its structure and properties.

On page 278 of this issue, Torkelson and co-workers[2] tackle two critical questions: "What is the size of the interfacial region?" and "how do the