

will require the simultaneous *in situ* observations of spreading and reaction. The design of such an experiment at high temperature is challenging. Perhaps reactive wetting could be investigated at room temperature with viscous polymers that also react with their substrate?

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MAGNETIC MEMORY

A signal boost is in order

Magnetic random-access memory (MRAM) has been touted as a universal memory with a wide range of potential applications in portable computers, consumer electronics and wireless devices. The use of certain combinations of materials that can now be deposited as thin-film layers with excellent crystalline order provides a significantly larger signal in the devices, and is expected to help advance the commercialization of MRAM.

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The prospect of a new generation of RAM technology to handle the growing demand for memory is pushing several research fronts in this area. Two papers in this issue on MRAM, one by Parkin and co-workers¹ and the other by Yuasa and co-workers², bring this goal one tangible step closer. To appreciate the advance their work represents, let us take a look at the current RAM landscape.

The ubiquitous dynamic RAM (DRAM) in present-day computers relies on storage of electric charge in a tiny capacitor, and must be refreshed on a millisecond time scale because of charge leakage. This causes numerous problems: significant time is required for starting up the computer because the operating system must be loaded from the disk drive; if power is lost unexpectedly, all of the work not saved to disk may be lost and the file system may be corrupted; the continual refreshing of the memory consumes power, which limits battery life in portable computing devices. Thus, there is an obvious need for non-volatile memory; that is, for a RAM (like the DRAM used in current computers) that does not require continual rewriting to retain stored information.

There are a number of candidates for such memory. Flash memory is a non-volatile RAM that is now widely used in portable devices such as cell phones, digital cameras and personal digital assistant devices. Unfortunately, flash memory is too slow

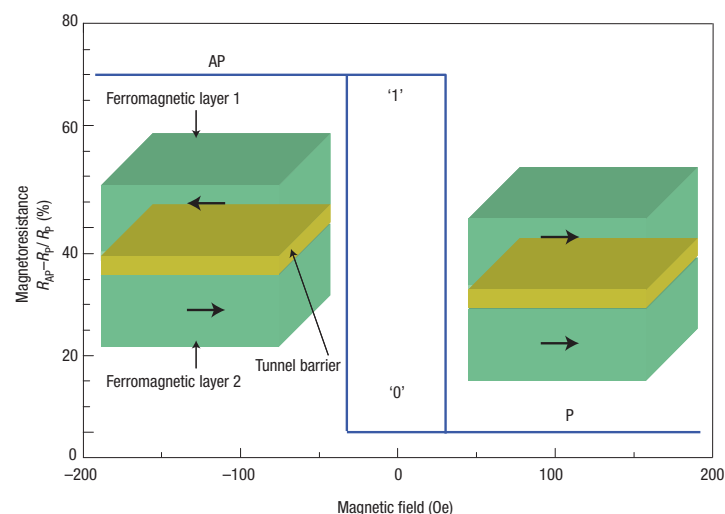


Figure 1 The 'switching' mechanism of a magnetic tunnel junction (MTJ). The MTJ used in MRAM devices consists of two electrodes — the two ferromagnetic layers — separated by an insulating tunnel barrier. A change in the tunnel junction resistance between the antiparallel (R_{AP}) and parallel (R_P) alignment of the magnetic layers, defined by the magnetoresistance, is observed by switching the relative spin orientation of the two electrodes. The high (R_{AP}) and low (R_P) resistance states correspond to '1' and '0' in the non-volatile memory device. It is easier to discriminate between these two states with larger observed resistance change.

— especially for writing — to serve as a replacement for DRAM. Another candidate to replace DRAM is FRAM (ferroelectric RAM). FRAM has been under development for many years, but it is still not clear

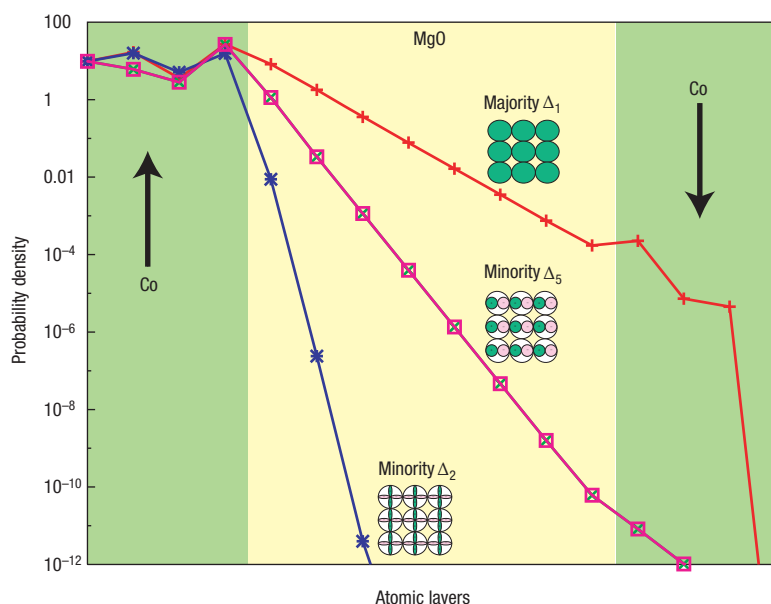


Figure 2 Theoretical calculation predicting very high resistance for the case of antiparallel moments of two b.c.c. Co electrodes⁸. The plot shows the probability density for electrons incident from the left. Electrons starting in the left layer as majority (spin up) are in the high-symmetry Δ_1 state, which decays relatively slowly within the MgO barrier. Electrons starting in the left layer as minority (spin-down) are in lower symmetry Δ_5 and Δ_2 states, which decay much more rapidly in the barrier. In the right Co layer, which has moments aligned oppositely to those in the left layer, the electrons which were injected from the left electrode as majority are now minority. They cannot propagate in the right electrode because no high symmetry Δ_1 state is available in minority b.c.c. Co. Similarly, electrons that were injected from the left electrode as minority become (locally) majority electrons when they enter the oppositely polarized right electrode. They also cannot propagate because neither Δ_2 nor Δ_5 states are available for majority spins. Thus neither majority nor minority electrons can propagate leading to a high resistance. For the case of parallel alignment of the magnetic moments of the two Co electrodes, the majority Δ_1 state can get through the barrier easily, and can propagate in both electrodes yielding a much lower resistance. Adapted figure printed with permission from ref. 8. Copyright (2004) by the American Physical Society.

whether FRAM memory cells will still function correctly after they have been written many millions of times. There is also a question of how well FRAM cells will scale to higher densities.

An important new contender for the goal of a non-volatile memory device is MRAM. In addition to non-volatility, MRAM promises to provide radiation hardness, non-destructive readout, very fast read and write speeds (<50 nanoseconds), low power consumption, as well as unlimited read/write endurance. These combined attributes make it very attractive as a universal memory technology with a potentially diverse range of applications in both stand-alone and embedded-memory devices.

A typical version of the MRAM architecture consists of an array of magnetic cells, each consisting of two ferromagnetic layers separated by an insulating barrier. The cells can be designed so that the magnetic moments of the two layers can either point in the same direction or in opposite directions. These two possible magnetic states — parallel or antiparallel — allow a bit of information to be stored. The orientation of the moments is controlled by magnetic fields generated by electrical currents.

The state of the system is read by using a relatively new phenomenon called tunnelling magnetoresistance (TMR), in which the electrical resistance measured between two ferromagnetic electrodes separated by an insulating barrier depends on their relative orientation. This is illustrated in Fig. 1. TMR arises from the well-known quantum-mechanical phenomenon of 'tunnelling'. The electrons in the metal electrodes do not have sufficient energy to get over the barrier formed by the insulator, so if they behaved as classical objects there would be no current, and the resistance would be infinite. Because electrons obey the laws of quantum mechanics, however, they can occasionally disregard the law of conservation of energy and 'tunnel' through the barrier.

MRAM began to be considered seriously when, in 1995, it was discovered by two groups that resistance changes of 10% or so could be obtained at room temperature when the relative orientation of the magnetic moments in the two ferromagnetic layers was switched^{3,4}. The key discovery was the observation that amorphous aluminium oxide barriers could be used to make pin-hole-free insulating tunnel barriers. Since then, the quality of the aluminium oxide barriers has been improved significantly so that the TMR measured — the change in resistance divided by the resistance for parallel moments — has increased to nearly 70%, which had been considered the theoretical maximum for the ferromagnetic electrodes used.

Some theorists^{5,6} had suggested that much higher values of TMR could be obtained by using crystalline rather than amorphous barriers. It was predicted⁵ that tunnelling through crystalline barriers of materials depends strongly on the symmetry of the wave functions at the Fermi energy. The electrons at the Fermi energy travelling along one of the principal crystalline axes in Fe, for example, exist in several states with different symmetries in the plane of the interface. It turns out that the states with the most symmetric wave functions can get through certain barriers much more easily than states with lower symmetry (Fig. 2). Some ferromagnetic materials, for example, body-centred-cubic (b.c.c.) Fe, FeCo and Co, have the property that the high-symmetry state is present for the electrons with majority spin but not for electrons with minority spin. When the moments are parallel, the high-symmetry majority electrons can get through the barrier and enter the electrode on the other side. When the moments are antiparallel, the high-symmetry majority electrons in one electrode can get through the barrier, but they cannot enter the electrode on the other side unless there is a scattering event that breaks the symmetry. The symmetries of the wave functions are indicated in Fig. 2.

The two papers^{1,2} both report observations that seem to confirm this effect and report very large values of TMR at room temperature. Yuasa and co-workers² used a process called molecular beam epitaxy to produce crystalline interfaces of Fe|MgO|Fe. They deposited the MgO at low oxygen pressure to reduce or prevent the oxidation of the Fe near the MgO interface — a problem that plagued previous attempts to observe large TMR in these systems. They observed a TMR of 180% at room

temperature, as well as oscillatory behaviour in the magnetoresistance as a function of film thickness, thus further affirming that the wave function is coherent across the tunnelling barrier. Parkin and co-workers¹ used sputtering to produce interfaces that are locally crystalline. In addition to pure Fe, they used a b.c.c. Co(Fe) alloy. The demonstration that large TMR values can be obtained by the sputter process is very important because that is the process most likely to be used for manufacturing commercial MRAM devices. Parkin's team report a maximum TMR of 220% at room temperature. In fact, they already attained this feat in 2002 (S. Wolf, personal communication) but patent considerations delayed the publication of their result.

The higher TMR signal produced by these new crystalline systems will make it much easier to produce a commercial MRAM device. If MRAM does turn out to be successful, it would be the second major spintronic device. The first one was the giant magnetoresistive sensor that is now used to read the magnetic bits stored on hard drives.

What does the future hold? There is still much to be understood about the new crystalline TMR devices. Theory predicts that even higher TMR should be achievable, especially at low temperature, by improving the interfaces and reducing the disorder. Also the rate of decay of the tunnelling current with the thickness of the barrier is slower than expected. This is good for applications, but not yet fully understood. There are

also more exotic materials that should be explored. Particularly interesting are the so-called half-metallic systems, such as CrO₂, which are simultaneously a metal for majority-spin electrons and an insulator for minority-spin electrons. These should, in principle, yield very large values of TMR even in the presence of disorder.

It has been suggested that MRAM cells can also serve as logic devices⁷. The ability to switch their state, for example from parallel to antiparallel and thereby change their electrical properties suggests that they could serve as field-programmable logic devices. Their significant advantage over present devices of this type would be a reprogramming time of the order of a few nanoseconds rather than milliseconds. One might even imagine a computer that instantaneously reconfigures itself to solve a given problem in the most efficient way. Such devices become more likely if we can further raise the TMR such that the cells function essentially as ON or OFF switches.

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MICROFLUIDICS

Magnetic chaperones for droplets

Iron oxide-doped photonic crystals are a simple means to wrap fluid droplets and control their movement. But they are also clever because they can be 'bar-coded' and have in-built sensing capabilities, which makes them exceptional candidates for microfluidic devices.

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The dream of replacing beakers, flasks, funnels, vials and all the standard equipment of a chemical or biomedical laboratory with a lab-on-a-chip is gradually becoming a reality¹. Reactions in microfluidic devices require minimal quantities of reagents, produce little waste, and can be very fast through integration with robotics and automation^{2,3}. The field of microfluidics is dominated by complex micro- and nanoscale channels etched or formed in a variety of solid materials⁴. The movement

of fluids through these tiny channels can be directed, for instance, by nanolitre pumps and capillary forces. This requires, however, substantial engineering and infrastructure. Even careful modelling cannot completely eliminate turbulence and shear when there are abrupt changes in channel direction or volume, or clogging of the channels due to precipitation⁵. In addition, on-chip, *in situ* analyses normally require the integration of substantial spectroscopic instrumentation with the tiny microfluidic chips.

On page 896 of this issue, Michael Sailor and co-workers describe a clever and adaptable self-assembly approach to manipulating microlitre-sized liquid droplets⁶. Using the same principles that govern the self-assembly of surfactant molecules at