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PERSPECTIVES

APPLIED PHYSICS: A New Twist for Magnets

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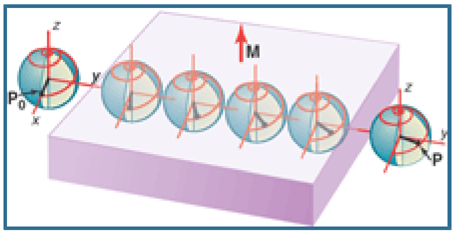
The manipulation of magnets with electrical currents is an integral part of everyday technology. It is the operating principle behind electric motors and determines how information is written onto magnetic-memory devices such as computer hard drives. The underlying physical mechanism has been understood since the early 1800s: Moving electric charges generate a magnetic field, which exerts a force on a magnet.

A surprising realization has recently emerged in this seemingly mature field. There is a second, fundamentally distinct mechanism by which an electric current can reorient a magnet, and for very small devices, this mechanism can be much more powerful than current-induced magnetic fields. The new mechanism, known as spin transfer, is based on the interaction of a magnet with the intrinsic spin of an electron, rather than with the electron's moving charge. On page 1015 of this issue, Weber *et al.* (1) report direct measurements of this spin-dependent interaction between an electron and the elemental ferromagnets iron, cobalt, and nickel.

Berger (2) and Slonczewski (3) first proposed such a spin-transfer effect. If an electron travels through a thin film of magnetic material, the magnet exerts a torque on the electron, tilting its spin. According to Newton's Third Law, the electron must exert an equal and opposite torque on the magnet, which causes the magnet's moment vector (the direction from its south to north pole) to tilt as well. The effect is called spin transfer because spin angular momentum is delivered from the electron to the magnetic material. The torque produced by a single electron is very small, but if all the electrons in a current are spin-polarized such that their spins all point in the same direction, then the sum of their contributions can produce a substantial torque on the magnet.

The existence of this effect was demonstrated recently in layered metallic devices (4-8). Electrons were first passed through a magnetic layer that acted as a spin filter to produce a partially polarized current. This current then produced a torque on a second magnetic element downstream. Depending on the device geometry and experimental conditions, the spin-transfer effect either can excite a dynamical state, in which a magnet's moment vector precesses continuously at frequencies of tens of gigahertz (4, 6-8), or it can cause simple switching of the magnet from one direction to another (5, 7-9).

Weber *et al.* (1) use a different experimental setup that permits quantitative measurements of the torque generated by an electron as it traverses a magnetic thin film. They use photoemission by circularly polarized light to eject fully spin-polarized electrons from a semiconductor cathode into a vacuum. These electrons are collected into a beam with an energy of a few electron volts and are shot through a suspended magnetic film that is a few nanometers thick. The original orientation of the electron spin polarization is selected to be perpendicular to the magnetic moment of the thin film (see the figure). By measuring the spin direction of the electrons that have passed through the film, the torque exerted by the magnet on the electrons can be determined. The (equal-and-opposite) torque of these electrons on the magnet is then also known.



Schematic geometry of the experiment of Weber ***et al*****.** When an electron passes through a magnetic thin film, the electron's spin precesses about the direction of the magnetic (**M**) moment of the film. At the same time, the electron spin direction also relaxes toward the spin direction of the majority electrons in the magnet. This means that the magnet and the electron apply spin-dependent torques on each other. $\mathbf{P_0}$ is the original electron spin direction; **P** is the electron spin direction after it has passed through the thin film.

Weber *et al.* can distinguish two separate effects: precession of the electron spin in a circle about the magnet's moment due to the exchange interaction inside the magnet and a simultaneous relaxation of the electron spin toward the magnet's moment due to spin-dependent scattering of electrons in the magnet (see the figure). Experiments as a function of magnetic film thickness allow both processes to be characterized with high accuracy. The torques are sufficiently strong that in a well-designed solid-state device, with current densities on the order of 10^{13} A/m^2, current pulses shorter than 10 ps should induce precessional magnetization reversal of a ferromagnetic device element.

Spin-transfer torques may allow magnets to be manipulated in ways that are impossible with traditional magnetic fields. Potential applications in high-density magnetic-memory devices, for instance, computer random access memory, are particularly exciting. As memory elements are scaled to sizes well below 1 μm, it is proving very difficult to control the orientation of the magnetic bits with the use of magnetic fields. On such small scales, very large current densities (approaching destructive levels) are needed to generate magnetic fields strong enough to produce magnetic switching. Furthermore, these fields decay slowly with distance, making it difficult to switch one magnetic element without disturbing its neighbors. Spin transfer has neither of these drawbacks. The spin-transfer effect can produce stronger torques per unit current than current-induced magnetic fields in devices much smaller than a micrometer, and spin-transfer torques extend only over atomic length scales. The additional ability of the spin-transfer effect to generate and control oscillations in magnetic materials in the tens of gigahertz range also opens possibilities for applications in high-speed logic and communications.

References

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