LAYERED MAGNETIC STRUCTURES: HISTORY, HIGHLIGHTS, APPLICATIONS

Once studied primarily for their effects on light, thin magnetic films are today being layered to make complex structures with unique magnetic properties. Devices based on these structures are revolutionizing electronic data storage.

Peter Grünberg

The study of layered magnetic structures is one of the hottest topics in magnetism today, due largely to growing applications in magnetic sensors and in magnetic storage media like computer disks and random-access memories (see the article by L. M. Falicov in PHYSICS TODAY, October 1992, page 46, and the special issue of PHYSICS TODAY on magnetoelectronics, April 1995). Magnetic random-access memories (MRAMs) based on structures of magnetic metallic films interspersed with nonmagnetic metallic or insulating interlayers could be the next generation in magnetic-storage technology, replacing the semiconductor-based dynamic random-access memories (DRAMs) that are now the standard. Advantages of MRAMs include nonvolatility (they retain information when the computer is switched off), high storage density, and low energy consumption. Until the introduction of DRAMs in the 1970s, MRAM technology—using minute ferrite rings, or "core"—was dominant. Thin magnetic film was suggested as a replacement for core as early as 1955, and the first research results were presented in 1959,[1,2] but problems with reliability of film-based MRAMs led instead to the adoption of DRAMs.

Now, almost a half century later, new discoveries are completely changing the situation. Phenomena such as giant magnetoresistance (GMR), tunneling magnetoresistance (TMR), exchange bias, interface anisotropy, and interlayer exchange coupling have given scientists a new toolbox with which to construct remarkable new devices.

An example of the kind of structures now being designed is the GMR-based sensor depicted in figure 1. The sensor uses changes in the resistivity of a layered structure to determine the orientation of an object; the sensor output, namely the variation in resistivity as a function of angle, is shown in the inset graph. The study of the physical properties of structures like those used in this sensor and the discovery of new techniques for fabricating these entities make up the field of layered magnetic structures. Ferromagnetic films can be combined with all kinds of other layers with different magnetic and electronic properties to obtain interesting and practical devices. GMR, TMR, and interlayer coupling all involve the transfer of spin-polarized electrons from one ferromagnetic layer across an interface to another, and studies of such processes are giving rise to whole new fields of study, including spin electronics and magnetoelectronics.

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Origins

The first studies of thin magnetic films were conducted in 1884 by August Kundt,[3] a German professor who is probably best known today for his pioneering work in determining the velocity of sound by measuring the ripples generated by sound waves on dust. Kundt fabricated thin films of iron, cobalt, and nickel, and was able to measure the rotation in the polarization of light transmitted through these films in a direction parallel to the film magnetization. The same kind of polarization rotation, now called the Faraday effect, was observed in 1845 by Michael Faraday, using a glass specimen in a magnetic field. Polarization rotation in light reflected from a magnetized surface was reported by John Kerr in 1876; the Kerr magneto-optical effect is also important today in research and applications involving magnetic films.

The interaction with light was the primary focus of ferromagnetic film research until about 1950. In the 1950s, development of computers led to a search for soft magnetic materials—materials that could relatively easily be made to reverse their magnetization direction—for use in information storage. The most promising candidate by 1955 was permalloy ($Ni_{0.8}Fe_{0.2}$), which had been shown to maintain its bulk soft-magnetic properties as a thin film. Permalloy could also be given a desired easy magnetization axis—the axis along which a material is most easily magnetized—by heat treatment in the presence of a magnetic field, a process called field cooling. Given the prospect of an application with a huge market (even in that pre-PC era), magnetic-film research activities exploded.

Initial applied research on MRAMs concentrated on the study of remagnetization, which is the essential process for writing information onto magnetic media.[2] Remagnetization can occur either due to rotation of the moments of elementary magnetic particles—described by the classic model of Edmund C. Stoner and E. Peter Wohlfahrt for systems with uniaxial anisotropy such as permalloy films—or as a result of movement of the domain walls. In thin films, domain structure and dynamics can be quite different from those in bulk materials. Bulk materials typically have Bloch-type domain walls, where the magnetization changes from one domain orientation to the next by rotating within the plane of the walls, but thin films often feature Néel-type domain walls, where the magnetization rotation is perpendicular to the wall plane. Thin films can also exhib-

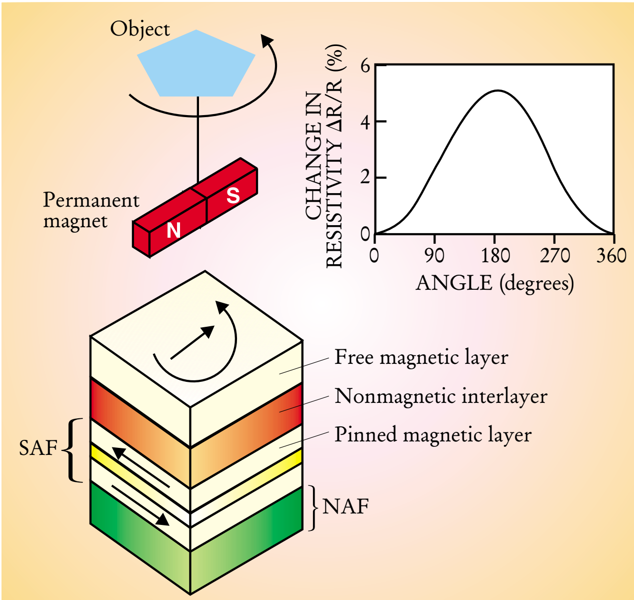


Figure 1. A layered magnetic structure used for a giant magnetoresistance-based field sensor to control rotating obects. The object (at top) is connected to a permanent magnet that rotates with it, causing a rotation in the magnetization of the free magnetic layer. The output of the sensor is the resistivity of the structure (inset graph), which, by the GMR effect, varies with the angle between the free layer magnetization and that of the pinned magnetic layer underneath. The lower layers of the structure serve to establish a directional orientation for the device: The natural antiferromagnet (NAF) on the bottom sets a preferred magnetization direction in the ferromagnetic layer just above it by exchange bias, and that layer is coupled through a nonmagnetic layer to the pinned magnetic layer above it by interlayer exchange coupling. The coupling of the latter two layers is antiferromagnetic, and the three middle layers comprise a synthetic antiferromagnet (SAF). The actual structure is much wider than it appears in the diagram. A sensor based on TMR instead of GMR would have an almost identical design, but with an insulating material in place of the metallic nonmagnetic interlayer.

it another kind of domain wall structure, cross-tie walls, which combine features of Bloch and Néel walls. Another feature of thin-film magnetization is nonuniformity in the magnetization within each domain, which appears in images as "magnetic ripples." A detailed description of domains and walls, including those in thin film structures, is given in reference 4.

The photograph on the cover of this issue displays an image of a section of a thin permalloy film showing domains separated by a cross tie wall and ripple-like fluctuations within the domains. The image was made using Lorentz microscopy, a method of transmission electron microscopy that exploits the deflection of electrons by Lorentz forces within the medium.[5] The structure of a cross-tie wall is sketched in figure 2: It may be regarded as a Néel wall having alternating intervals of oppositely directed senses of rotation of the magnetization within the wall.

Early studies on thin film structures revealed the phenomenon of exchange bias,[6] through which an antiferromagnetic layer can cause an adjacent ferromagnetic layer to develop a preferred direction of magnetization. This anisotropy, associated with the exchange anisotropy at the interlayer interface, is produced by heating the structure to above the Néel temperature (the maximum temperature of antiferromagnetic ordering) but not as high as the Curie temperature. Exchange bias was first seen in 1956 in fine Co particles: After the particles were heated, producing an outer layer of antiferromagnetic Co oxide, then cooled in the presence of a magnetic field, the hysteresis loop for magnetization of the oxide-coated particles was found to be shifted. Similar observations of magnetization bias were soon made in thin films. Exchange bias is often used in sensors like the one shown in figure 1 to pin the magnetization in a desired direction.

Fundamental properties

Fundamental physics research has been conducted using magnetic films, often with practical benefit. Thin films are ideal for studying the transition between two-dimensional and three-dimensional behavior, studies that can shed light on the collective processes that give rise to magnetism; such studies can also lead to better designs for high-density information-storage media. Very thin films have such a low density of magnetic particles that they approach the superparamagnetic limit, the maximum information density that can be stored before thermal fluctuations overwhelm the magnetic ordering. Magnetic storage in the not-too-distant future will confront this limit. In addition, the dimensionality of the structure determines important material properties, such as the direction of magnetization. High-density computer disks often use magnetization perpendicular to the disk surface to reduce interference between domains.

An important indicator of the transition from bulk to 2D behavior is the temperature dependence of the saturation magnetization $M_S(T)$, a readily measured quantity important for extrapolating ground-state properties from finite-temperature measurements. The dependence of the magnetization curve of a thin film of $Ni_{48}Fe_{52}$ on film thickness is shown in figure 3; the curve becomes more linear as the film thickness is decreased, while at the same time the Curie temperature T_c decreases.[7] Such behavior is not surprising because magnetism is a collective phenomenon due to the exchange interaction, where nearest neighbors contribute most. Experiments have shown that the thin-film crystal structure, which determines the number and distance of nearest neighbors, is an important determinant of magnetic behavior. For example, a close-packed Fe-(110) monolayer on tungsten is fer-

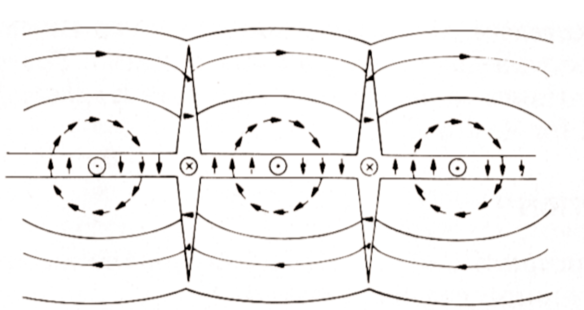
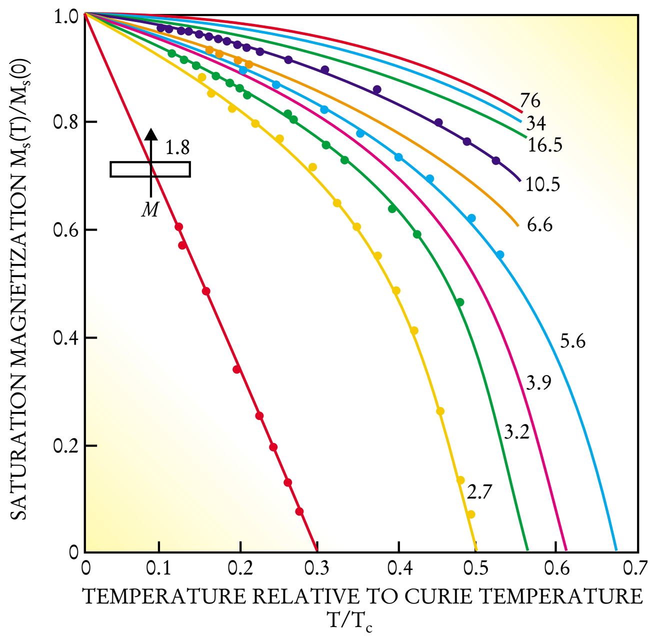


Figure 2. Sketch of cross-tie domain walls, a hybrid type of domain wall often found in thin films. The lines with arrows depict the magnetic field lines both outside and inside the wall. A Lorentz microscopy image of cross-tie walls in a permalloy film is shown on the cover of this issue.

FIGURE 3. THIN FILMS APPROACH TWO-DIMENSIONAL behavior, as seen in the temperature dependence of the saturation magnetization $M_S(T)$ in thin films of $Ni_{48}Fe_{52}$. The temperature is normalized to T_c, the Curie temperature of the bulk material. Curves are labeled by the film thickness in monolayers; a single monolayer thickness is 2.04 Å. As the film is made thinner, its magnetization curve should (and does) become more linear. The magnetization direction is within the plane of the film, except for the thinnest film (1.8 monolayers), for which the magnetization is perpendicular to the film plane—a surprising discovery (Adapted from Gradmann, reference 7).



romagnetic, with a Curie temperature of T_c = 225 K when uncovered, or T_c = 282 K when covered with gold. An Fe(100) monolayer, however, where the nearest neighbors of the corresponding bulk structure are missing, appears not to order magnetically. Adding a second layer to this structure fills in the nearest neighbors and restores ferromagnetic behavior with T_c = 220 K—not much different from the 225 K observed for the (110) monolayer.

Whereas reducing the film thickness reduces T_c in ferromagnetic films of Fe, Co, and Ni, it has no corresponding effect on the low-temperature saturation magnetization, which generally remains unchanged and sometimes even increases (although interaction with nearby material can occasionally cause a net decrease). An increase reflects the transition in thinner films from a bulk metal to a collection of more isolated atoms. In bulk Fe, Co, and Ni, the magnetic moments are well described with a model of itinerant electrons and energy bands, but in ultrathin films of these materials, the bands are narrower and the energy balance shifts to favor a particular electron spin orientation, thereby increasing the magnetization.

Near the Curie temperature, the magnetization is related to the temperature by a simple power law $M \propto (1 - T/T_c)^\beta$, where the critical exponent β is a sensitive indicator of the dimensionality of the system. For 3D systems, β should be 0.325–0.365, whereas for 2D systems β should be 0.1–0.15, depending on the model used. Critical behavior close to the Curie temperature has been well-studied; one such study in thin Ni films found that β changes abruptly from 0.29 to 0.17 when the thickness is decreased from 7.5 to 5 monolayers, indicating a transition from a 3D to a 2D system at a thickness of approximately 6 monolayers.[8]

Another important discovery is noted on the plot in figure 3: perpendicular orientation of the magnetization with respect to the sample plane for a 1.8-monolayer film of $Ni_{48}Fe_{52}$. When first observed in 1968, this phenomenon was attributed to a surface anisotropy that had been predicted by Néel in 1954. (A similar effect observed two years earlier in a Ni film had been attributed to magnetostriction, but the $Ni_{48}Fe_{52}$ alloy was chosen to exclude magnetostriction.) The Néel anisotropy is due to symmetry breaking and can be predicted from data on bulk anisotropy and magnetostriction. However, the Néel explanation is not the only possibility. Using extensive numerical calculations, a group at Philips Research Laboratories in Eindhoven, the Netherlands, predicted a strong interface anisotropy with easy axis perpendicular to the sample plane in a Co/Ni multilayer structure.[9] The interface anisotropy arises from spin–orbit coupling and is related to the electronic band structure of the layers. Further support for this model came from measurements of a $(Co1/Ni2)_{20}$ structure, where the notation indicates 20 repetitions of a basic structure consisting of one Co monolayer and two Ni monolayers. The structure, with a relatively large total thickness of 120 Å, showed strong perpendicular anisotropy (figure 4).[9]

While predicted by theory, this result was a surprise for experimentalists. Thick films tend to have in-plane magnetization because the magnetostatic energy, which favors this alignment, increases linearly with film thickness for an infinitely wide film. Typically, interface anisotropy causes such films to order perpendicular to the sample plane only for thicknesses below approximately 1 nm (see also figure 3). Another cause for surprise was that an interface anisotropy between ferromagnetic films had not been considered possible.

Variations on—and possibly improvements of—known structures can be produced by substitution of related elements. For example, palladium and platinum lie below Ni in the periodic table and so have the same number of valence electrons; replacing Ni with Pd or Pt in the $(Co1/Ni2)_{20}$ structure ought to result in a structure with similar properties—with, for example, a similar induced interface anisotropy. The strength of an anisotropy is usually expressed in terms of the areal energy density associated with the anisotropy; we can choose the sign so that negative anisotropy energy density favors magnetization perpendicular to the film plane and positive favors in-plane magnetization. The interface anisotropy energy density E_S is about –0.3 mJ/m² for the Co/Ni interface and –0.9 mJ/m² for the Co/Pd interface. In these structures, the other major contribution to anisotropy energy is the form anisotropy energy E_D; for a monolayer of Co, E_D = 0.25 mJ/m². Thus, for a many-monolayer Co film with a Pd interface, the total anisotropy energy density $E_S + E_D$ changes sign for Co thickness between 3 and 4 monolayers, with thinner films having perpendicular magnetization. Experiments have borne out this simple model.

Applications

The first proposals for computer memory based on patches of permalloy films failed, at least for large-scale applications, in part because the remagnetization curve for the films lost its squareness after many write cycles due to edge domains that could not be adequately removed by the small applied fields available. This problem still exists

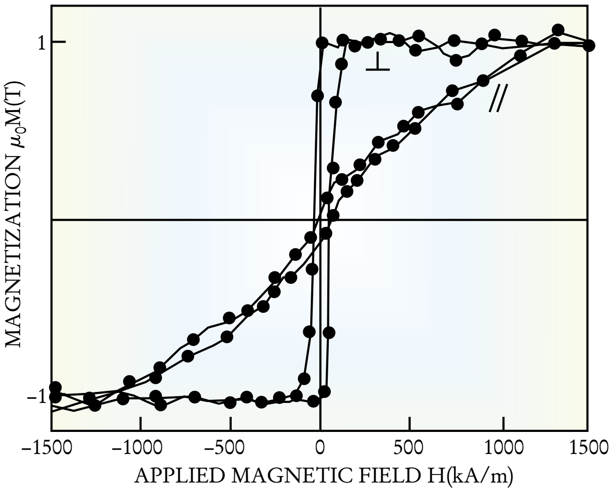


FIGURE 4. STRONG PERPENDICULAR ANISOTROPY is evident in the remagnetization (hysteresis) curves of the layered structure $(Co1/Ni2)_{20}$, constructed using 20 repetitions of a sequence of one monolayer of Co and two monolayers of Ni. For a field H applied perpendicular to the plane, the magnetization increases and saturates rapidly, whereas for a parallel applied field the magnetization saturates only at approximately 1500 kA/m.

in modern film-based MRAMs, but, as discussed later, more tools are now available to deal with it. Although they didn't succeed for RAM applications, thin magnetic films have found other uses in data storage as a replacement for another kind of magnetic material: fine magnetic particles. Thin films of cobalt–platinum–tantalum alloys with coercivities on the order of 300 mT and thicknesses of a few tens of nanometers are now the standard in computer hard disks, and magnetic particle-based storage is still widely used only in magnetic tapes.

Another application for thin magnetic films is magneto-optical recording, first developed in 1958 using manganese–bismuth films. Magneto-optical data storage uses materials that are magnetically hard at room temperature but relatively easily remagnetized at a moderately high temperature. To record data, a laser heats a small spot on the recording material that is then cooled in the presence of a magnetic field; the same laser can be used to read the magnetized spots by means of the Kerr magneto-optical effect. Information is stored in cylindrical domains magnetized in one of the two possible directions perpendicular to the sample plane. Rare earth garnets have been favored for magneto-optical recording since the mid-1960s. One advantage of these materials is that some composites exhibit a "compensation point," a temperature below the Curie temperature where the net magnetization goes to zero. Information stored at this point is particularly stable.

Work on rare earth garnet materials led to the discovery in 1967 of the "magnetic bubbles" that dominated research on data storage during at least the decade that followed. Bubbles are small cylindrical domains that can be produced in films with perpendicular anisotropy. In suitable ferrite or garnet films, they combine high stability with large mobility and so can be used to store and shift data. Magnetic bubbles typically are seen in relatively thick materials (thicknesses on the order of a few microns) and so are somewhat outside the scope of this article.

In 1973, magneto-optical research began focusing on rare earth–transition metal (RE–TM) films. The large magneto-optical interaction in the transition metals allows especially thin films to be made from these materials. With suitable composition and preparation techniques, RE–TM films can be made with compensation points and perpendicular anisotropy; even bubbles have been observed. Despite a vulnerability to corrosion, RE–TM alloys at present seem to be unchallenged for applications like magneto-optical minidisks.

New discoveries

By the mid-1980s, new evaporation techniques for fabrication and improved diagnostic tools had prepared the way for new discoveries. The big discoveries of that time were interlayer exchange coupling (IEC)[10] and GMR.[11,12]

IEC is an interaction between two ferromagnetic layers separated by a nonmagnetic metallic spacer that, for small external fields, causes the layers' magnetization to align either ferromagnetically (parallel) or antiferromagnetically (antiparallel), with the coupling showing an attenuated oscillation as a function of spacer thickness. IEC was first reported in 1986 for layered structures of dysprosium and gadolinium separated by a yttrium spacer and for iron films separated by a chromium spacer.

The GMR effect is a dramatic variation of the electrical resistivity with applied magnetic field; it was observed two years after the first IEC reports in antiferromagnetically exchange-coupled Fe/Cr structures (figure 5). For GMR, the resistivity is high in the absence of an external field, but as the external field grows in strength, it forces the initially antiparallel magnetizations of the coupled layers into parallel alignment, and the resistivity drops. It was soon found that IEC is not a necessary precondition for GMR, which can also be seen in decoupled structures, such as those in figure 1. The only requirement for GMR is a rotation, by whatever means, in the magnetizations of adjacent ferromagnetic films with respect to each other.

The applications potential of the new effects, particularly GMR, was immediately recognized by researchers, who began an intense search for combinations of materials showing GMR or IEC. Experiments soon demonstrated that films of ferromagnetic $3d$ metals, such as Fe, Ni, and Co, show strong coupling effects when combined with interlayers of $4d$ and $5d$ transition metals, such as ruthenium, rhodium, iridium, and rhenium. This result is believed to be due to the similar band structures and the magnetic upshift of spin-down bands in the $3d$ metals, which result in a strong contrast in the spin-dependent reflectivity at the $3d/4d$ and $3d/5d$ interfaces. The arguments concerning band structures are similar to those used earlier in this article to explain the strong interface anisotropy at Co/Pt and Co/Pd interfaces. To date, the maximum GMR effect reported is an 80% reduction in resistivity for multilayers and a 20% reduction for trilayers at ambient temperature. In 1990, it was finally shown that IEC is a general phenomenon and that it is oscillatory as a function of the thickness of a metallic interlayer.

Various theoretical descriptions of IEC and GMR have been proposed. An early approach for IEC was to postulate an interaction similar to the Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling that has been observed between magnetic impurities. The RKKY theory involves exchange coupling between the magnetic moments in the layers and the spin of the conduction electrons in the interlayer, and correctly predicts an oscillatory interlayer coupling. Another description of IEC was based on a postulated spin-dependent reflectivity of electrons at the layer interfaces. The reflectivity confines conduction electrons in the interlayer, and the electron motion perpendicular to the sample

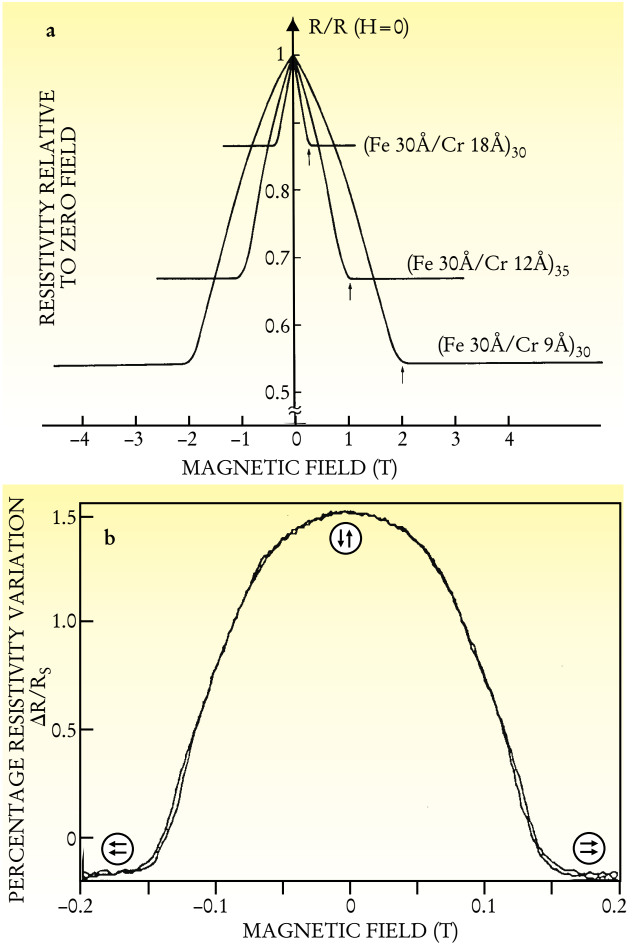


FIGURE 5. FIRST OBSERVATIONS OF GMR in two different types of layered systems. The plots show changes in resistivity as a function of applied magnetic field. **(a)** The ratio of the measured resistivity to the zero-field resistivity for three different Fe/Cr multilayers, with structure as indicated—for example, (Fe 30 Å/Cr 12 Å)$_{35}$ denotes a structure built from 35 copies of a sandwich of a 30 Å layer of Fe and a 12 Å layer of Cr. The arrows indicate the saturation magnetic field for the structure. (Adapted from Baibich et al., ref. 11.) **(b)** The percentage change in resistivity of a Fe/Cr/Fe trilayer from the value R_S at saturation magnetic field along the easy axis. At high field magnitudes, $R - R_S$ is negative because the resistivity is further lowered by anisotropic magnetoresistance. The circled arrows indicate the directions of the magnetization in the Fe layers. (Adapted from Binasch et al., ref. 11.)

plane is described by standing waves with discrete energy levels. Increasing the interlayer thickness causes these energy levels to successively "dive" through the Fermi level and become populated; because the magnetic alignment of the confining ferromagnetic films is influenced by the energy level occupancy, the coupling oscillates with interlayer thickness. Another theoretical description by John Slonczewski[13] (recently verified experimentally) is based on spin currents; a very interesting consequence of this theory is that currents between the magnetic layers could be used to switch their magnetization by means of a current-induced coupling.[14]

Whereas IEC is thought to be mainly due to spin-dependent reflectivity, the main mechanism for GMR is considered to be spin-dependent scattering. The notion dates back to Nevill Mott, who theorized that, in the presence of a magnetic field, the total current can be viewed as consisting of two components flowing in parallel, one with spin up (parallel to the magnetization) and the other with spin down (antiparallel to the magnetization). Directional quantization ensures that only parallel and antiparallel spin orientations need be considered and that a given orientation cannot be easily inverted by a spin-flip process. Electrical resistivity is proportional to the electron scattering rates: If scattering rates for spin-up and spin-down electrons are different, then the resistivities of the two kinds of currents will also be different, a theory known as Mott's two-current model. Figure 6 illustrates how the two-current model relates magnetization and resistivity in a layered structure of two ferromagnetic films (light yellow) separated by a metallic but nonmagnetic interlayer (orange). For parallel layer magnetizations (figure 6a), half of the current effectively has a short circuit and the resistivity is significantly reduced from that with antiparallel alignment.

We assume in figure 6 that spin-down electrons are scattered and spin-up electrons are not, but the mechanism just described explains the reduced resistance regardless of which spin orientation is scattered. Which electrons, then, are scattered more, and why? This is actually a complicated question because in real ferromagnetic materials, the conduction bands shift with magnetic field so that spin-up and spin-down electrons have quite different properties. (A remarkable example of this shift with potentially important applications in magnetoresistivity is the class of half metallic magnets, discussed in the article by Warren Pickett and Jagdesh Moodera on page 39.) However, some kind of spin-dependent conductivity is certainly plausible.

Spin-dependent scattering is not the only possible explanation of the GMR effect. Other contributing processes could be spin-dependent reflectivity and changes in electronic properties of the medium due to the layering, such as the so-called quantum well states.

Robotics, memories, and strain

The GMR effect has turned out to be very useful for sensors, particularly those for read heads in computer hard-disk drives. Use of thin films for hard drives was first introduced in 1979 by IBM—the coil in the read sensor was made using thin film technology, although at that time the reading and writing processes were still inductive. In 1992, sensors based on the anisotropic magnetoresistance (AMR) effect were introduced for read heads and contributed to an annual storage-capacity growth rate of about 60% (AMR sensors exploit the difference between resistivity parallel to and that perpendicular to the magnetization). AMR-based sensors have now been replaced by GMR sensors because the GMR effect is larger and GMR sensors can be more compact—an important consideration when trying to squeeze as much information as possible into a limited disk platter area.

Other potential applications for GMR lie in robotics and in sensors to control mechanical movements (for example, in cars). The system in figure 1 is an example of such a device, capable of monitoring the rotational motion of an object. The primary advantage here of using the GMR effect is that the full rotational angle can be measured. An AMR-based sensor, by contrast, could not distinguish between two magnetization directions separated by 180°. The sensor is also a good application for antiferromagnetic interlayer coupling, which is the basis of the

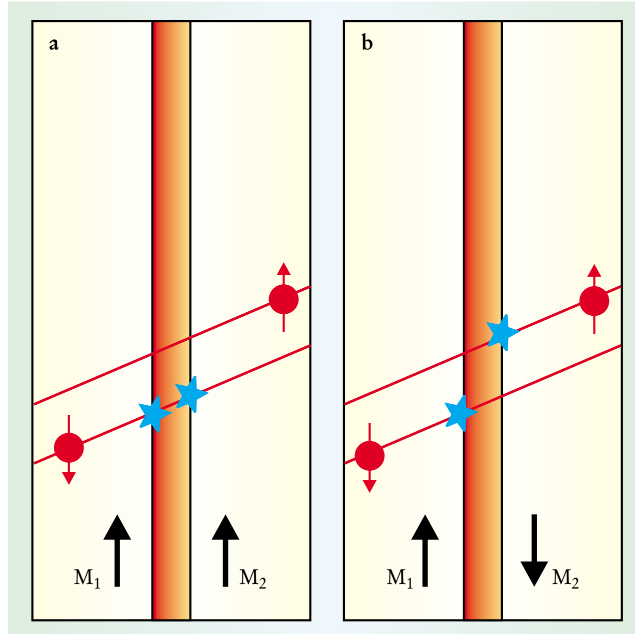


FIGURE 6. SPIN-DEPENDENT SCATTERING is believed to underlie the variation of conductivity with the relative orientation of magnetizations in coupled layers. Cross sections of a stucture of two ferromagnetic films (yellow) are shown, having magnetizations M_1 and M_2 in the directions indicated by arrows, and separated by a nonferromagnetic interlayer (orange). The net current flow is from bottom to top, but the conduction electrons (red dots with an arrow denoting the spin orientation) drift randomly within and between the layers. For simplicity, it is assumed that only electrons with their spins antiparallel to the local magnetization are scattered. (**a**) With parallel M_1 and M_2, spin-down electrons are scattered while spin-up electrons flow freely in a "short circuit." (**b**) With antiparallel M_1 and M_2, both spin-down and spin-up electrons are scattered.

SAF structure. An antiferromagnet structure is useful here because, with zero net magnetic moment, it interacts minimally with external magnetic fields. By itself, the SAF could respond to moderate external fields by changing its orientation via a spin-flip transition, which is the reason that in the figure 1 sensor the SAF orientation is pinned by a NAF.

Noncompensated synthetic ferrimagnets (SFs) with finite net magnetization have also been constructed in the same way as SAFs. Potential applications of SFs have been identified for sensors and magnetic recording media.

Galvanic separation of signals—presently the domain of optocouplers—is an attractive application for GMR because of the high sensitivity and small size of GMR devices. Galvanic separation reduces electrical noise and grounding problems by transmitting a signal across an electrically insulating region; using GMR-based sensors, magnetocouplers can be designed that use the fields naturally produced by the signal currents, without the need to convert the electrical signal into an optical one.

The discovery of GMR and its many potential applications has also led to a revival of interest in the tunneling phenomenon of TMR.[15] In fact, TMR was the first magnetoresistance effect discovered in which interfaces were essential elements—it was first measured by M. Julliere in 1975—but strong interest grew only in the early 1990s, when increased values for TMR were reported. TMR structures have the same form as GMR structures, but for TMR the interlayer material is insulating rather than conducting. In TMR, a voltage applied between ferromagnetic films causes a tunneling current to flow across the interlayer with a magnitude that depends on the relative orientation of the magnetizations on both sides of the interlayer. As with GMR, the resistance is higher for antialignment.

Most applications for which GMR can be used are also candidates for TMR. In some cases, TMR appears to perform better than GMR: For double layers, record values for TMR of around 50% have been reported at room temperature[15] compared to 20% for GMR in the same kind of double-layer system. Nonetheless, for many applications other considerations—including noise, reproducibility, and fabrication costs—might make GMR preferable to TMR. It was mainly the resurgence of the TMR effect that inspired the revival of the old MRAM idea (discussed earlier), in which TMR would serve as a low-power basis for readout.

The most recent MRAM proposals are based on both GMR and TMR. One GMR-based MRAM cell[16] has a structure similar to the stack shown in figure 1, except that the structure is cylindrical (a stack of ring-shaped layers). Current along the axis would set the magnetization either clockwise or counterclockwise in the soft magnetic layers of the cell; axial current could be used to read the information in the cell by sensing the GMR-related change in resistivity with magnetization. Numerical simulations have indicated that the cell would operate with complete remagnetization and no degradation of stored information, even after many cycles. Another way of switching the magnetization direction would be to use the current-induced interlayer coupling described previously.

Other applications of layered magnetic structures take advantage of the interaction of magnetic and mechanical properties such as magnetostriction or its inverse. If a film with large enough magnetostriction is deposited on a nonmagnetic substrate, the whole structure will bend if the magnetization is rotated. This effect can be used for switches or actuators, such as in micropumps that are controlled by an external magnetic field. On the other hand, inverse magnetostriction can be used for strain sensors. If a layered structure is built of materials with different magnetostrictive constants, application of stress will cause the magnetizations in different layers to rotate relative to each other. If the materials also display a GMR effect, then the stress can be detected via the change in resistivity associated with the rotation.

New frontiers

Phenomena like magnetization-related changes in electric resistivity and electric current-induced magnetic interlayer coupling can be considered to be part of a new field called magnetoelectronics, spin electronics, or simply spintronics, in cases where spin injection is the most important process. Spin injection is important, for example, in GMR and interlayer coupling processes, where electrons injected across the interlayer must have well-defined spin orientation and spin orientation is conserved during interlayer transport. Thin films of layered magnetic structures are often, although not always, used in such studies and the resulting applications.[17]

The rules that govern spin injection and interlayer coupling are still being investigated. For example, interlayer coupling across semimetals, semiconductors, and some insulators is often strong but nonoscillatory, in contrast to the oscillatory dependence on interlayer thickness seen with IEC. It has been theorized that spin injection is very difficult to achieve between ferromagnetic layers separated by a thick semiconductor interlayer (requiring almost complete spin polarization in the ferromagnetic material)[18] but recent results by Rashid Gareev and collaborators at the Jülich Research Center in Germany show both oscillatory and very strong nonoscillatory interlayer exchange coupling for Fe films with very thin silicon interlayers, with the coupling depending on the Fe doping of the Si. There is still much to learn about the nature of the coupling across semimetal, semiconductor and even insulator interlayers, and how such coupling is related to the better-understood oscillatory coupling across metallic interlayers.

The field of layered magnetic structures is broad and still expanding, with many different phenomena of interest. It remains a fascinating field, rich with opportunities both in basic research and in potential applications.

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