

SPIN-POLARIZED TRANSPORT

Electrons have spin as well as charge, and this may make all the difference in future electronics.

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A new field that has come to be called “spin-polarized transport” is growing dramatically. Although its roots are in the quantum description of solids, only recently have new material fabrication techniques permitted widespread study of the phenomenon and the development of device applications (see figure 1).

The notion that the carriers of current in a ferromagnetic metal, such as Fe, Co or Ni, should themselves be magnetically polarized dates from the earliest realizations that ferromagnetism is essentially a quantum mechanical effect arising from the spin of the electron and that magnetic moments reflect an imbalance between up and down spins. From figure 2 this is easy to see. In this simple representation of the density of states available to the electrons, a normal metal such as copper has equal numbers of electrons with up and down spins. Therefore it has no net moment, and the current-carrying electrons at the top of the filled states, called the Fermi level, are unpolarized.

However, a ferromagnetic metal, to avoid the high energy of having a high density of states at the Fermi level, has a splitting between the up and down spin states, called “exchange splitting,” which lowers the total energy of the system. Here there is a spin imbalance, as illustrated in figure 2 for cobalt, with the up-spin (or majority) d-electron states all filled and the d-electron states at the Fermi level containing entirely down-spin (minority) electrons. The moment of Co is simply proportional to the difference between the occupations of the two spin bands available. Although there are also s and p electrons at the Fermi level, a significant number of the carriers are the more highly polarized d electrons, which should produce a current that is partially spin polarized.

Tunneling experiments

The earliest attempts to test these ideas were quantum tunneling experiments in which normal metals were used as contacts and the current was passed through “spin filters”—barriers whose conductance depends upon spin.¹ None of these early tests were as definitive or elegant as the experiments reported in 1970 that first measured the spin polarization of the current originating in a ferromagnetic metal film.² In these experiments, electrons tunneled through a nonmagnetic insulating barrier film into

a superconducting metal film that acted as a “spin polarized” detector when a magnetic field H was applied to the structure, as figure 3a shows. The applied field defines the orientation of the magnetic moment and therefore the spin direction in the magnetic film. It also splits the sharply peaked density of states in the superconducting film into spin-up and spin-down states separated by an energy of $\pm \mu H$, where μ is the electron spin magnetic moment. By careful analysis of the currents $I_{\uparrow}$ and $I_{\downarrow}$ transmitted through the tunneling barrier into the superconductor’s spin states, as a function of voltage and applied magnetic field, the experimenters determined the percentage polarization of the current. This fraction, defined as

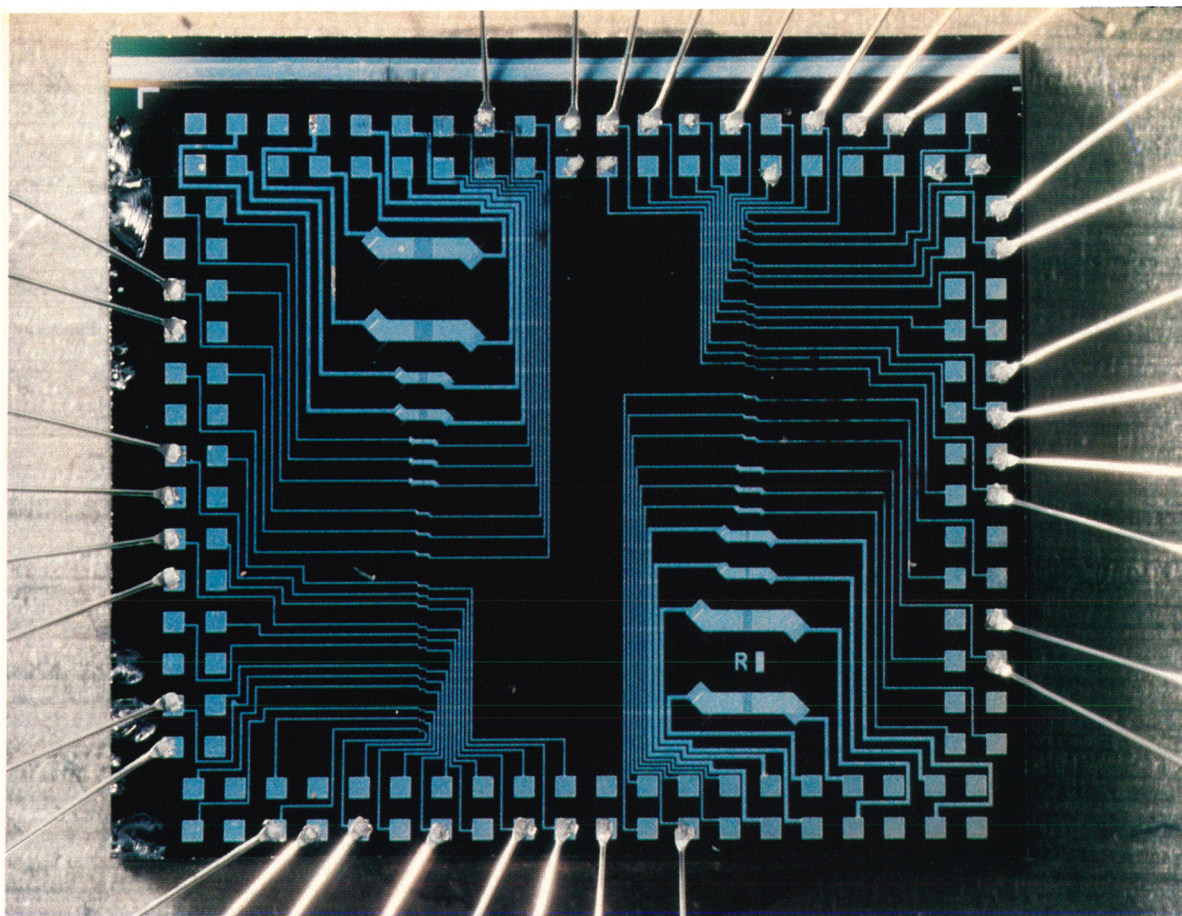
$$P = \frac{I_{\uparrow} - I_{\downarrow}}{I_{\uparrow} + I_{\downarrow}}$$

was determined to be 44% for iron, 34% for cobalt and 11% for nickel.

These results were surprising, because they scaled not with the polarization of the electrons at the Fermi level (as indicated in figure 2) but rather as the total moment given by the net polarization of the electrons. Furthermore, the sign of the polarization was the reverse of that expected! This uncomfortable state of affairs lasted for several years, through repeated attempts at understanding, until it was shown by detailed analysis of a more realistic spin-resolved band structure that one must carefully identify those d electrons that participate in the tunneling current (itinerant electrons) and those that do not (localized electrons).³ This was an early indication that spin-polarized transport could give large effects but that understanding these effects would require detailed knowledge of the electronic structure of the materials.

An important advance was made in 1975, a few years after these successful spin-polarized tunneling experiments were reported.⁴ Instead of analyzing the spin polarization of the tunneling current using a superconducting film in an applied field, experimenters replaced the superconducting film with another ferromagnetic metal film, as figure 3b illustrates. It was reasoned that electrons originating from one spin state at the Fermi level of the first film would be accepted by unfilled states of the same spin at the Fermi level of the second film. If the two ferromagnetic films were magnetized parallel to each other, then minority electrons would go into minority states and majority electrons would pass into majority states. If, however, the two films were magnetized in opposite directions, the identity of majority and minority would be reversed and minority electrons from the first

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MICROCHIP containing lithographically defined elements ranging in area from 1 to 10^4 square microns. The elements are used to measure giant magnetoresistance perpendicular to the plane of the chip. **FIGURE 1**

film would seek empty majority states in the second, just as majority electrons from the first film would seek minority empty states in the second. One can see that if the simple density-of-states model in figure 2 is accurate, the parallel arrangement should yield much higher conductance through the barrier than does the antiparallel arrangement.

This is in fact what was observed. A 14% change was seen in the conductance for tunneling through a Ge barrier at low temperature using Fe and Co ferromagnetic films for the two layers. This "magnetic valve" effect straightforwardly exploited the dependence of spin-polarized transport upon the spin-dependent density of states available at the Fermi level in the two ferromagnetic metal films. In operation, it is analogous to passing light through crossed polarizers; however, here minimum transmission is obtained when the magnetic moments of the two magnetic films are rotated 180° away from parallel, whereas for the optical case minimum transmission is obtained from a 90° orientation of the two polarizer axes.

This is a consequence of the spin's being the source of the magnetization and the $\cos^2(\theta/2)$ dependence, which comes from the spinor transformation when one projects one spin state onto another whose coordinate axis is rotated an angle θ from the first. Within the last year, experiments using high-quality thin film structures have unequivocally demonstrated⁵ the "spin filter" effect with EuSe barriers and have observed⁶ a tunneling polarization of 24% between ferromagnetic films through Al_2O_3 .

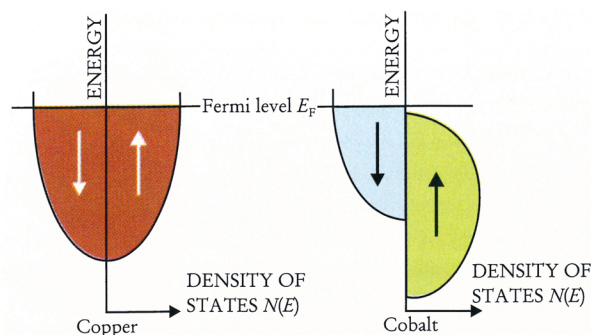
Tunneling experiments need not be carried out be-

tween two metal films separated by an insulating barrier layer. Surface science research that led to the development of the scanning tunneling microscope showed that electrons could tunnel through a vacuum barrier. This observation has led to several efforts around the world to carry out spin-polarized vacuum tunneling experiments. It is known, for example, from both spin-polarized photoemission and secondary-electron emission studies on magnetic materials that an electron emitted from a magnetic surface enters the vacuum with its spin direction unchanged. This important result permits the study of spin-polarized electronic states as well as the imaging of micromagnetic domain structures of magnetic materials using electron physics techniques, as E. Dan Dahlberg and Jian-Gang Zhu show in their article on page 34.

Thus one might expect spin-polarized vacuum tunneling to be a straightforward technique in which one merely replaces the nonmagnetic tunneling tip with a ferromagnetic one. Unfortunately, a reliable method for obtaining a well-defined spin state at the atomic limits of the tunneling tip has proven elusive, and reproducible results have been difficult to achieve.

Spin relaxation

Having established that one can generate spin-polarized carriers, the next most important issue is to determine how long these electrons remember their spin orientation. This is especially important for electronic applications, because if the spins relax too rapidly, the distances traversed by the spin-polarized current in a device will be too



DENSITY OF STATES $N(E)$ in copper and cobalt, represented schematically. Here the electron energy E is measured from the Fermi level E_F , the top of the filled states. **FIGURE 2**

short to serve any practical purpose.

Fortunately, the fundamental quantum mechanical nature of spin places it out of reach of many of the forces in a solid. Its principal means of interacting are through exchange coupling with other electrons in the vicinity of a magnetic atom or via spin-orbit coupling to impurity atoms or defects. In the absence of these influences, the orientation of a carrier's spin can be very long-lived, even though the carrier may undergo many scattering events.

This issue was first confronted in 1955, by both theory and experiment. The context of the research was the excitation of a nonequilibrium population of spin-polarized electrons in the skin depth of a normal metal when microwave radiation is absorbed in an electron-spin resonance experiment, and the diffusion of these electrons from the skin into the bulk of the metal.⁷ A spin diffusion length L_s was defined in terms of the electron diffusion constant D such that the generated spin imbalance would relax over a length $L_s = D\tau_s$, where τ_s is the spin relaxation time. These concepts were explored over the next 20 years through magnetic resonance line-shape studies. It became clear that the spin relaxation time should be sufficiently long in some metals at low temperature that one could measure the spin diffusion length directly through a transport experiment, using ferromagnetic metal contacts to inject spins into a normal metal.

A successful experiment was finally reported in 1985. This experiment measured the spin diffusion length of carriers injected into a paramagnetic metal from a ferromagnetic contact.⁸ The stunning result, that this length was 0.1 mm at 40 K in aluminum, showed that spin-polarized currents could travel distances comparable to those in modern electronic device structures without losing "memory" of their spin orientation.

Magnetoresistance in ferromagnetic metals

It may at first seem reasonable to expect that one could change the resistance of a ferromagnetic metal itself by applying a magnetic field. However, because the effective internal magnetic field seen by an electron inside a ferromagnetic metal—arising from the metal's own magnetization—is thousands of times larger than the available fields, the principal effect of an external field is merely the reorientation of the internal magnetization direction.

For example, the anisotropic magnetoresistance measures the change in resistance seen when the current flowing through a sample changes from being parallel to the internal magnetization to being perpendicular to it. The observed change depends upon the applied field only insofar as the field is sufficient to rotate the direction of magnetization in the sample. In permalloy ($\text{Ni}_{0.80}\text{Fe}_{0.20}$), a common material for anisotropic magnetoresistance device applications, this change $\Delta R/R$ is about 2%. A much more dramatic effect has been observed in single-crystal

iron whiskers. In the absence of an applied field, these whiskers typically distribute their internal magnetization into magnetic domains, which orient themselves into a pattern of minimum energy configuration of little or no net magnetic moment. In an applied field strong enough to align all of these domains (saturation field), it was found⁹ that at low temperatures the resistance change $\Delta R/R(H=0)$ was about 600%!

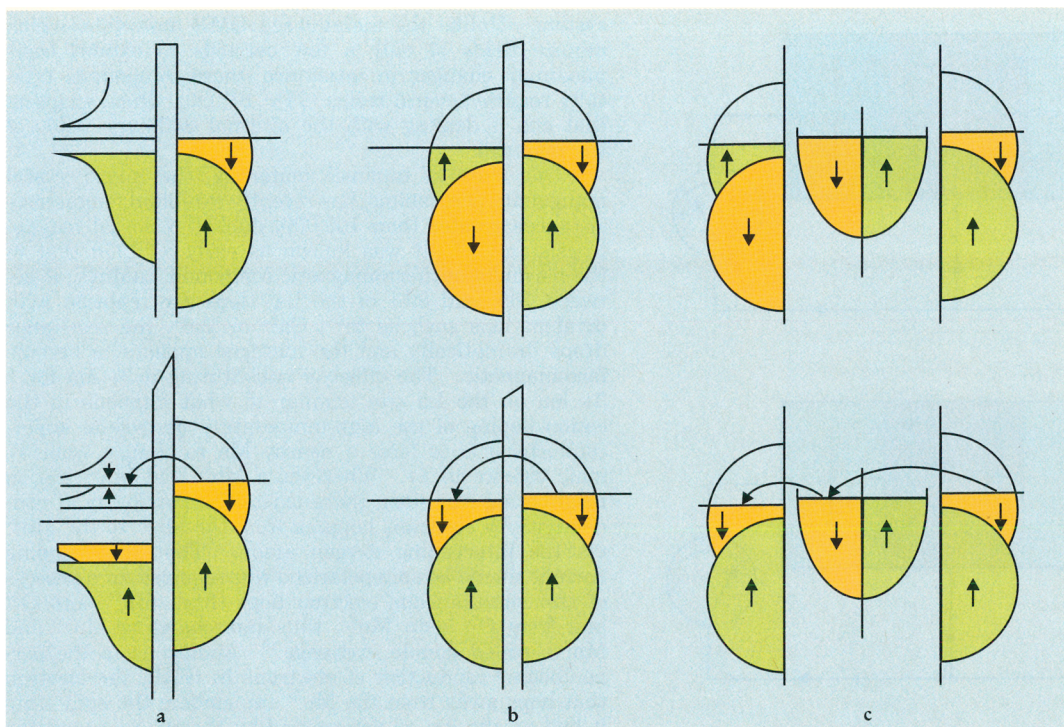
In spite of these dramatic magnetoresistance effects, single-crystal magnetic metal whiskers are hardly attractive for large-scale applications. On the other hand, the anisotropic magnetoresistance of permalloy, especially in the form of films, has been employed for a number of uses, from sensors in magnetic-bubble memory chips to non-volatile thin film computer memory and high-density read heads. (See John Simonds's article on page 26.) Therefore the world of magnetoelectronic applications was very receptive when the discovery of "giant magnetoresistance" in multilayered metallic film structures brought a new class of magnetoresistive materials into being.

Giant magnetoresistance

Giant magnetoresistance is a term coined to describe the behavior of materials consisting of alternating layers of ferromagnetic and nonmagnetic metals deposited on an insulating substrate.¹⁰ The resistance, measured by current flowing parallel to the layers, is greatest when the magnetic moments in the alternating layers are oppositely aligned and smallest when they are all parallel. This change was measured to be 100% in the original paper reporting giant magnetoresistance, and the most recent record is 220% at low temperatures.¹¹ The largest effects are seen with Fe-Cr or Co-Cu alternating layers, and the effect increases with the number of layers up to the limits quoted, which are reached for approximately 100 repeats at layer thicknesses of a few nanometers.

Giant magnetoresistance and anisotropic magnetoresistance are both typically observed in a given sample; however, giant magnetoresistance can be a much larger effect. GMR, as contrasted with AMR, depends only upon the relative orientation of the magnetic moments of the layers. Although an external magnetic field is applied to change this relative orientation, in the absence of AMR there is no dependence upon the orientation of the magnetic moments to the direction of current flow.

Experiments to test the dependence of the GMR effect upon the relative orientation of moments in simple sandwich structures—consisting of two ferromagnetic layers separated by a normal metal—show that the GMR effect scales simply as the projection of the magnetic moment of one layer upon the magnetic moment of the other. As the earlier tunneling experiments showed, this is a result of the well-known spinor transformation of elementary quantum mechanics and indicates that the resistance



THREE CLASSES OF EXPERIMENTS represented by schematic diagrams of their densities of states. Curved arrows show electron flow. **a:** Tunneling through barrier from ferromagnetic film on right to superconducting film on left. The top figure is for zero applied magnetic field H and no applied voltage; the bottom figure is for $H \neq 0$ and applied voltage. **b:** Tunneling through barrier from one ferromagnetic film into another ferromagnetic film. The top figure is for moments in anti-aligned films; the bottom figure is for moments in aligned films. **c:** Transport through nonmagnetic metal from one ferromagnetic film into another ferromagnetic film. The top and bottom figures are as in b. **FIGURE 3**

derives from electron scattering events that are spin defined.

Theorists have taken several approaches to identifying and describing these events.¹² The events themselves fall into two categories: spin-defined scattering at interfaces where the films meet, and spin scattering within the interior (bulk) of the films. A great deal of experimental effort has gone into identifying which of these categories is more important, and it is now becoming clear that for homogeneous layers the spin scattering is primarily at the interfaces.¹³ However, magnetic defects within the interior of a film, such as magnetic impurities in the nonmagnetic metal layer or inhomogeneity within the ferromagnetic layer, can also contribute measurable spin scattering.

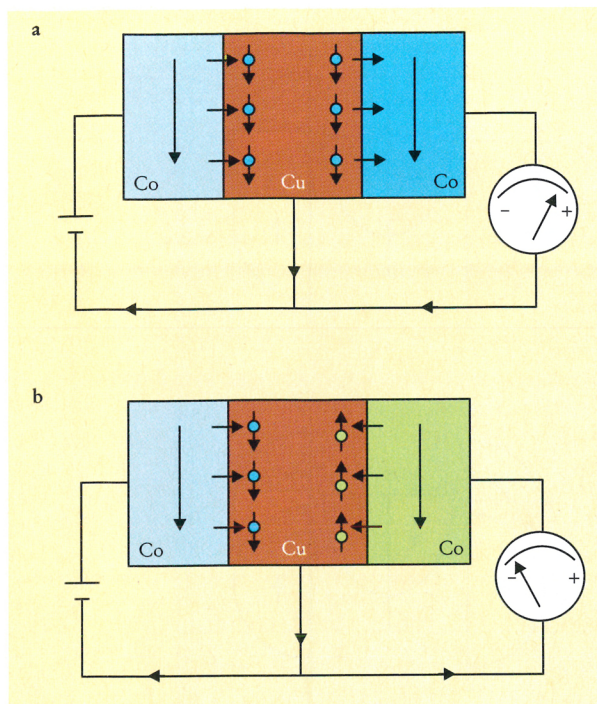
More recent experiments to measure GMR have been carried out in a perpendicular geometry, as shown in figure 3c, reminiscent of the earlier tunneling experiments. The perpendicular geometry yields larger effects, because there is no shunting of the current through normal metal layers; all of the current must undergo spin scattering at every interface to traverse the layered structure. However, the low resistance of all-metal structures requires either ultrasensitive SQUID voltmeter techniques¹⁴ or lithographic fabrication of elements with very small cross-sectional areas.¹⁵ Both of these techniques have been used successfully. Furthermore, the lithographic fabrication of small structures, which exhibit large effects at room temperature, indicates its potential usefulness in integrated applications (which require submicron-sized devices), be-

cause $\Delta R/R$ is independent of the cross-sectional area.

A more immediate benefit of the perpendicular transport experiments is in their clarification of the physics of the transport process. Theoretical treatment of the parallel transport geometry data is made difficult by the role that interface roughness plays in the scattering process. Perfectly smooth interfaces would give rise to only specular scattering, which would generate no interfacial impedance—spin dependent or otherwise. Because the roughness of buried interfaces continues to be one of the most difficult properties to either characterize or control, it has proved difficult to make quantitative contact between theory and experiment.

In the perpendicular geometry, however, useful theoretical treatments are possible.¹⁶ It has proved to be an excellent approximation to assume that the current is carried by two nonintermixing components, spin up and spin down, and that one need only determine the spin-scattering coefficient for each of these components at the interfaces and in the interiors to completely describe the magnetoresistance behavior of a multilayered structure. The spin relaxation length itself has proved to be much longer than the typical 1–10-nm layers in most structures. This means that a given electron can pass through many layers before “forgetting” its spin orientation. Within this length, each magnetic interface can act as a spin filter, and the more scattering interfaces an electron interacts with, the stronger the filtering effect. This explains the increase of the GMR effect with the number of layers.

Finally, the interfacial spin scattering itself must



SPIN TRANSISTOR scheme. Current flow in the three-terminal, bipolar device is shown for aligned (a) and anti-aligned (b) magnetic moments in the two ferromagnetic films. **FIGURE 4**

ultimately derive from the degree to which the conduction bands at the Fermi level are well matched at the interface. This is also easy to see in principle from the bulk band states. For Fe–Cr, the two bcc structures are lattice matched and the (paramagnetic) d-conduction band of Cr closely matches the minority (spin down) d-conduction band of Fe; there is no close match to the conjugate Fe majority (spin up) d-conduction band. This suggests severe discrimination between up and down electrons at this interface, leading to the large GMR effect observed. There is a similar band matching of majority spin bands at the interface between the two fcc structures in Co–Cu, the other main system that exhibits a large GMR effect.

An additional development in these metallic systems avoids the use of layered structures entirely. Recent work in granular GMR¹⁷ has found large effects in materials formed by cold deposition of immiscible metals, such as Co and Cu, which are then annealed to permit the growth of ferromagnetic Co particles within a Cu matrix. At an optimum particle size, one sees GMR arising from the spin-dependent scattering of electrons at the Cu–Co interfaces, and the changes in resistance are seen to follow the alignment of the particles' moments in an applied magnetic field. As the particles grow larger, the ratio of surface to volume decreases, and the GMR effect decreases.

Magnetoresistance in insulators

The discovery of giant magnetoresistance in artificially fabricated metal multilayers and granular alloys has revived interest in other materials that exhibit connections between magnetism and transport properties. In fact, very large magnetoresistances were observed long ago in compounds in which the effect is intrinsic to the material and a function entirely of the magnetic order of the spin

system. Unlike the metal-based GMR materials, which require fields of only a few oersteds to exhibit their maximum changes in resistance, these compounds typically require several teslas ($1\text{T} = 10^4\text{ Oe}$), which suggests that one is dealing with the internal exchange fields of the material.

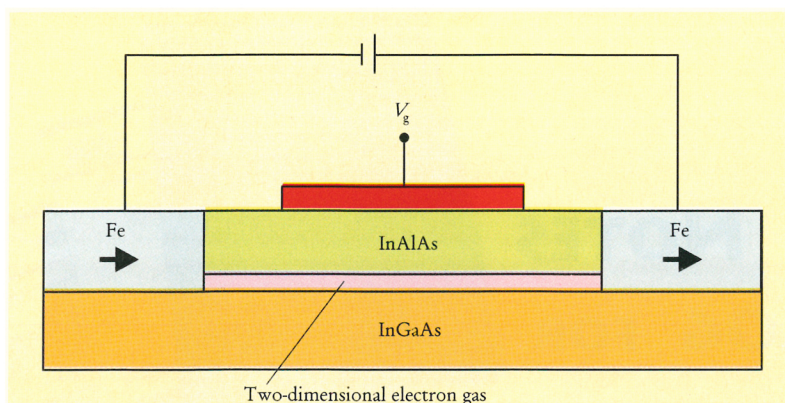
One class of intrinsic materials, the mixed-crystal manganate perovskites, has recently exhibited magnetoresistances greater than 100 000, dubbed "colossal magnetoresistance."¹⁸ It was known as early as 1950 that in the normally antiferromagnetic compound LaMnO_3 , if between 10% and 50% of the La^{3+} ions are replaced with divalent ions such as Sr^{2+} , Ca^{2+} or Ba^{2+} , the resistance drops dramatically and the material appears to become ferromagnetic. The effect of substituting a 2+ ion for a 3+ ion on the La site (similar to what happens in the cation doping of the high-temperature perovskite superconductors) is to force a nearby Mn to change from 3+ ionic valence to 4+. Wherever a Mn^{3+} and Mn^{4+} are on neighboring Mn sites, there exists the possibility of conductivity by electrons hopping from the Mn^{3+} to the Mn^{4+} via the intervening oxygen anion. That this hopping current should be spin polarized was required for a process of two simultaneous electron hops (from Mn^{3+} onto O^{2-} and from O^{2-} onto Mn^{4+} , thus interchanging Mn^{4+} and Mn^{3+}), called double exchange.¹⁹ Analogous to the perpendicular conduction of electrons in GMR, the electron that hops away from the Mn^{3+} remembers the spin state it had on the ion as determined by Hund's rule, and the electron hopping onto the Mn^{4+} must have the same spin state. This is only possible, without violating Hund's rule on the Mn^{4+} , if the net ion spins of the neighboring Mn^{3+} and Mn^{4+} are in the same direction. In fact, the likelihood of electron hopping between two magnetic ions turns out to depend on the spinor transformation, $\cos(\theta/2)$, where θ is the angle between their spin directions. Thus the resistance of the material becomes a function of its intrinsic magnetic order.

Because LaMnO_3 is known, from neutron diffraction work done more than 40 years ago, to be a layered antiferromagnet, it is tempting to think of these mixed-crystal systems as atomic-scale analogs of tunneling—that is, an applied field aligns the spin directions between adjacent layers and permits (hopping) conductivity. Fortunately, today there are techniques available to probe the local ionic spin structure in detail, and it should be known very soon if this simple picture is adequate or if more subtle magnetic effects play a role.

Spin accumulation

A final important concept involved in spin-polarized transport is the shift of subband chemical potential that accompanies the accumulation of spin-polarized electrons in a normal metal. A kinetic picture is natural for describing the resistive effects in GMR structures, which have layer thicknesses less than an electronic mean free path, so that interfacial spin-dependent scattering is a large fraction of all electron scattering events. However, structures with thicker layers (on the order of 100 nm or more) have easily defined chemical potentials and are best described in the language of thermodynamics.

When spin-polarized current is driven from a ferromagnetic film into a nonmagnetic film faster than the spin polarization can diffuse away from the interface, a nonequilibrium population of spin-polarized electrons builds up in a region of thickness L_s . This nonequilibrium magnetization is described as inequivalent chemical potentials for the up-spin and down-spin subbands of the normal metal. The chemical potential of the ferromagnet, however, is held in equilibrium by the intrinsic ferromag-



SPIN-POLARIZED field-effect transistor scheme. V_g is the gate voltage. **FIGURE 5**

netic–nonmagnetic metal interface; this is the same as an internal electric field, associated with the nonequilibrium spin accumulation, that tries to drive electrons back across the interface and into the ferromagnet. Because spin and charge are both carried by the electron, a gradient of spin density results in an electric field, which can generate current flow or produce differences in voltage.²⁰

These effects have been demonstrated in an interesting device arrangement called a spin transistor, shown in figure 4.²¹ It is a three-terminal, bipolar device consisting of a normal metal sandwiched between two ferromagnetic metal layers. Current is driven from the first ferromagnetic film (emitter) into the nonmagnetic metal (base) and back through the battery. A symmetric circuit arm connecting the second ferromagnetic film (collector) to the base contains a current detector.

If the magnetic moments of the two ferromagnetic layers are parallel, spin accumulation in the base will create an electric field that pushes current into the collector, generating a positive current in the detector arm of the circuit. If, however, the magnetic moments are antiparallel, the spin-accumulation electric field at the base–collector interface has the opposite sign, current is pulled from the collector into the base, and a negative current is generated in the detector arm. The current flow through the detector can thus undergo bipolar modulation by modulating the direction of magnetization in the second layer. The device may be thought of as a nonvolatile computer memory element, storing information via the orientation of the second layer.

A device that has been proposed but not yet demonstrated applies the spin-injection concept to a semiconductor structure, yielding a spin-polarized field-effect transistor.²² Figure 5 is a schematic diagram of a spin FET. The current-carrying medium would be an inversion layer formed at the heterojunction between InAlAs and InGaAs. The two-dimensional electron gas in that layer would provide a very high-mobility channel, free of spin-flip scattering events. The spin-polarized carriers are injected and collected by ferromagnetic metal pads, as discussed above. However, one can expect a strong internal electric field to be present in the heterostructure interface region in the inversion layer, oriented perpendicular to the layer. This field induces an interface spin–orbit effect on the carriers in the channel moving parallel to the interface, which will cause the spins of the carriers to precess. This precession will rotate them out of alignment with the magnetization of the second ferromagnetic pad, decreasing the transmitted current of the device. Finally, if a gate electrode is deposited on top of the device, one can apply a gate voltage V_g to increase or decrease the effective electric field, altering the spin precession. This will con-

trol the alignment of the carriers' spin with respect to the magnetization vector in the second pad, thus permitting modulation of the current passing through the device. While this proposed device demands carefully controlled material growth and lithography, its fabrication is well within the reach of existing technology.

Although the field of spin-polarized transport can trace its origins back nearly 50 years, it is still in its infancy. It has provided us with a new viewpoint both for understanding the electronic properties of solids and for exploiting these properties to generate new effects. These effects will soon be the basis for electronic devices in the new field of magnetoelectronics.

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