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Magnetoelectronics

Gary A. Prinz

An approach to electronics is emerging that is based on the up or down spin of the carriers rather than on electrons or holes as in traditional semiconductor electronics. The physical basis for the observed effects is presented, and the initial successful applications of this technology for information storage are reviewed. Additional opportunities for the exploitation of this technology, which are currently under study, are described.

Basic research in the physical sciences, especially in condensed matter physics, can result in important developments in applied physics and engineering. One example was the discovery of transistor action in Ge (observed at Bell Labs in December 1947), which ultimately developed into the solid state electronics industry. It is remarkable that the first commercial Ge transistors were available in 1952, just 5 years after the initial discovery.

A recent example of a rapid transition from discovery to commercialization, which has occurred in spin-polarized electronic transport, is the giant magnetoresistance effect (GMR), as applied to magnetic information storage. GMR is a quantum mechanical effect observed in layered magnetic thin-film structures that are composed of alternating layers of ferromagnetic and nonmagnetic layers. When the magnetic moments of the ferromagnetic layers are parallel, the spin-dependent scattering of the carriers is minimized, and the material has its lowest resistance. When the ferromagnetic layers are antialigned, the spin-dependent scattering of the carriers is maximized, and the material has its highest resistance. The directions of the magnetic moments are manipulated by external magnetic fields that are applied to the materials. These materials can now be fabricated to produce significant changes in resistance in response to relatively small magnetic fields and to operate at room temperature. The widely cited report of the discovery of GMR appeared in 1988 (1). Although the first commercial product using GMR (a magnetic field sensor) was available in 1994 (2), the first products to have a major economic impact are "read" heads for magnetic hard disk drives, which were announced by IBM in November 1997 (3). The market for these products is estimated to be on the order of \$1 billion per year and will increase the storage on a disk drive from 1 to 20

gigabits, merely by the incorporation of the new GMR materials. The next major economic impact from the discovery of GMR is anticipated to come from nonvolatile magnetic computer memory. Honeywell Corporation announced the demonstration of GMR random access memory (RAM) in January 1997 (4). If GMR RAM development continues as rapidly as the development of GMR read heads, one can anticipate a major impact on the RAM market, which is currently measured worldwide at \$100 billion annually.

Spin-Dependent Transport

Spin-polarized transport will occur naturally in any material for which there is an imbalance of the spin populations at the Fermi level. This imbalance commonly occurs in ferromagnetic metals because the density of states available to spin-up and spin-down electrons is often nearly identical, but the states are shifted in energy with respect to each other (Fig. 1). This shift results in an unequal filling of the bands, which is the source of the net magnetic moment for the materials, but it can also cause the spin-up and spin-down carriers at the Fermi level to be unequal in number, character, and mobility. This inequality can produce a net spin polarization in a transport measurement, but the sign and magnitude of that polarization depends on the specific measurement being made. For example, a ferromagnetic metal may be used as a source of spin-polarized carriers injected into a semiconductor, a superconductor, or a normal metal or can be used to tunnel through an insulating barrier. The nature of the specific spin-polarized carriers and the electronic energy states associated with each material must be identified in each case.

The most dramatic effects are generally seen for the most highly polarized currents; therefore, there are continuing efforts to find 100% spin-polarized conducting materials. These are materials that have only one occupied spin band at the Fermi level. Materials that are only partially polarized [such as Fe,

Co, Ni, and their alloys, which have a polarization P of 40 to 50% (5)] are, however, adequate to develop technologically useful devices. P is defined in terms of the number of carriers n that have spin up ($n \uparrow$) or spin down ($n \downarrow$), as $P = (n \uparrow - n \downarrow)/(n \uparrow + n \downarrow)$.

Because of the spin polarization of an electron current, the effects seen in solid state devices can be most readily visualized if one assumes that the current is 100% polarized (Fig. 1). In that case, the only states that are available to the carriers are those for which the spins of the carriers are parallel to the spin direction of those states at the Fermi level. If the magnetization of the materials is reversed, the spin direction of those states also reverses. Thus, depending on the direction of magnetization of a material relative to the spin polarization of the current, a material can function as either a conductor or an insulator for electrons of a specific spin polarization. An analogy can be made with polarized light passing through an analyzer. However, in the optical case, crossing the polarization axis at 90° prevents the transmission of the light, whereas for spin-polarized electrons, the magnetization must be rotated 180° to stop electrical conduction.

Device Principles

The basic action in a spin-polarized device is shown in Fig. 2, where it is assumed that the electrons are traveling from a ferromagnetic metal, through a normal metal, and into a second ferromagnetic metal. When the magnetizations (or, equivalently, the magnetic moments) of the two ferromagnetic metals are in an aligned state, the resistance is low, whereas the resistance is high in the antialigned state. Actual devices are not generally fabricated in the orientation shown in Fig.

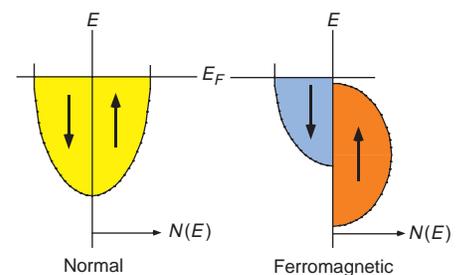


Fig. 1. A schematic representation of the density of electronic states that are available to electrons in a normal metal and in a ferromagnetic metal whose majority spin states are completely filled. E , the electron energy; E_F , the Fermi level; $N(E)$, density of states.

The author is at the Naval Research Laboratory, Washington, DC 20375, USA.

2, because they are made from thin films and the resistance perpendicular to the plane is too low. The common orientation, shown in Fig. 3, provides more useful resistance, but the physical picture of the spin-polarized transport is more complicated. The effect of the spin exclusion in antialigned films is still observed, but it results in high interface scattering and "channeling" of the current into narrowed pathways (Fig. 3). When the films become aligned, both of these resistance-generating mechanisms are removed, and the device resistance decreases.

This simple two-layer system is commonly referred to as a "spin valve" and is constructed so that the magnetic moment of one of the ferromagnetic layers is very difficult to reverse in an applied magnetic field, whereas the moment of the other layer is very easy to reverse. This easily reversed (or "soft") layer then acts as the valve control and is sensitive to manipulation by an external field. The device can be used to measure or monitor those fields and can have numerous applications.

Magnetic Recording

The first application to produce a substantially large economic impact was that for the read heads in magnetic disk recorders, which are components of every computer. The read head senses the magnetic bits that are stored on the media (disks or tapes). This information is stored as magnetized regions of the media, called magnetic domains, along tracks

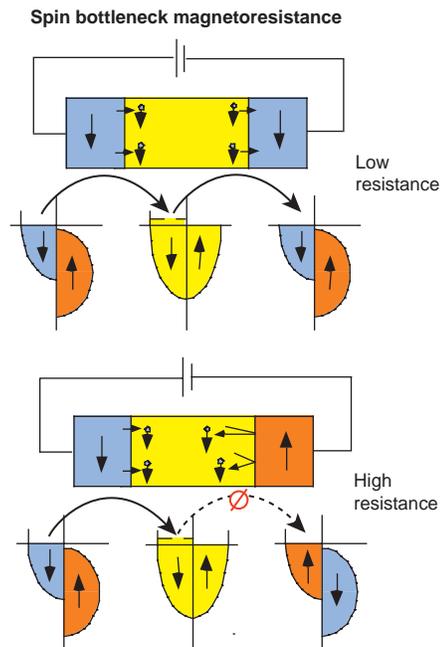


Fig. 2. Schematic representations of spin-polarized transport from a ferromagnetic metal, through a normal metal, and into a second ferromagnetic metal for aligned and antialigned magnetic moments. \emptyset , disallowed channel.

(Fig. 4). Magnetization is stored as a "0" in one direction and as a "1" in the other. Where two of these oppositely magnetized domains meet, there exists a domain wall, which is a microscopic region of 100 to 1000 Å (depending on the material used in the media). Although there is no magnetic field emanating from the interior of a magnetized domain itself, uncompensated magnetic poles in the vicinity of the domain walls generate magnetic fields that extend out of the media. It is these fields that are sensed by the GMR element. Where the heads of two domains meet, uncompensated positive poles generate a magnetic field directed out of the media, and where the tails of two domains meet, the walls contain uncompensated negative poles that generate a sink for magnetic lines of flux returning back into the media.

The element is fabricated (6) so that the magnetic moment in the easily reversed layer lies parallel to the plane of the media in the absence of any applied fields. The magnetic moment in the fixed magnetic layer of the GMR element is oriented perpendicular to the plane of the media. Thus, when the head passes over a positive domain wall, the magnetic field pushes the easily reversed magnetic moment up, and when the head passes over a negative domain wall, the magnetic moment is pulled down. The measured resistance of the GMR element thus increases (for more antialigned layers) or decreases (for more aligned layers). The design goal for this element is to obtain a maximum rate of change in the resistance for a change in the sensed field. Typically, changes in resistance of 1% per oersted are reported.

Nonvolatile Memories

The next application that is expected to have a large economic impact is nonvolatile memory. "Nonvolatile" refers to information storage that does not "evaporate" when power is removed from a system. Magnetic disks and tapes are the most widespread nonvolatile

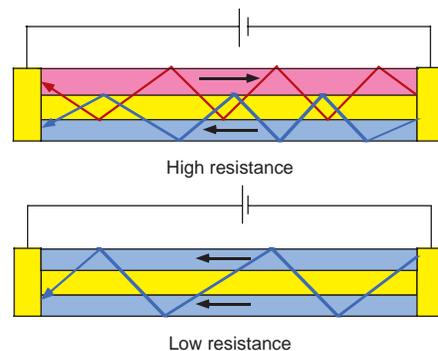


Fig. 3. Schematic representations of transport that is parallel to the plane of a layered magnetic metal sandwich structure for aligned (low resistance) and antialigned (high resistance) orientations.

information storage media, because of their long storage lifetime, low cost, and lack of any wear-out mechanism. Computer core memory itself was nonvolatile before the introduction of semiconductor RAM in the early 1970s. The original core memory acquired its name because it was assembled from magnetic transformer cores, which were fabricated out of insulating magnetic ferrite materials. These transformer cores were tiny toroidal rings that were threaded with fine copper wires. Current pulses through the wires could magnetize the cores either as right- or left-handed to store a 0 or a 1; each core was a bit. The information was read by current pulses, which could test the core's direction of magnetization through an inductively induced pulse in another wire. Although this memory was slow and expensive and had low density by today's standards, it was the industry standard during the 1950s and 1960s and had the advantage that, when power was removed, the stored information remained intact.

Honeywell has recently demonstrated (4) that GMR elements can be fabricated in arrays with standard lithographic processes to obtain memory that has speed and density approaching that of semiconductor memory, but is nonvolatile. An example of the structure of such an array is shown in Fig. 5. The GMR elements are essentially spin-valve structures that are arranged in series connected by lithographic "wires" to form a "sense line." The sense line stores the information and has a resistance that is the sum of the resistance of its elements. Current is run through the sense line, and amplifiers at the ends of the lines detect changes in resistance in the elements. The magnetic fields needed to manipulate the magnetization of the elements are provided by additional lithographically defined wires above and below the elements, which cross the sense lines in an *xy* grid pattern, with intersections at each of the GMR information storage elements.

These individual networks of lines are all electrically insulated, but when current pulses are run through them, they generate magnetic

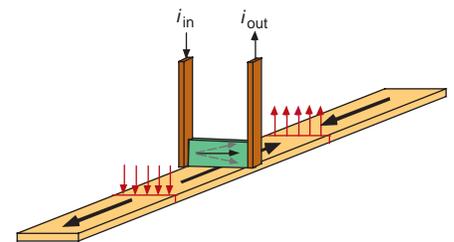


Fig. 4. A schematic representation of a GMR read head (green) that passes over recording media containing magnetized regions. The magnetization direction of the soft layer in the head responds to the fields that emanate from the media by rotating either up or down. The resulting change in the resistance is sensed by the current i passing through the GMR element.

fields that can act on the magnetic elements. A typical addressing scheme uses pulses in the overlay and underlay lines (commonly called "word lines" and "bit lines") that are "half-select" (that is, the field associated with a word-line pulse is half that needed to reverse the magnetization of a spin-valve element). Where any two lines in the xy grid overlap, however, the two half-select pulses can generate a combined field that is sufficient to selectively reverse a soft layer or, at higher current levels, sufficient to reverse a hard layer also. Typically, one pulse rotates the layer 90° , and the second pulse completes the task by rotating it the remaining 90° . Through this xy grid, any element of an array can be addressed either to store information or to interrogate the element.

The exact information storage and addressing schemes may be highly varied. One scheme may store information in the soft layer and use "destroy" and "restore" procedures for interrogation. Alternatively, another scheme could construct the individual GMR elements so that high-current pulses are used to store information in the hard layer. Low-current pulses can then be used to "wiggle" the soft layer to interrogate the element by sensing the change in resistance, without destroying and restoring the information. There are many additional variations on these schemes, and the exact scheme used is often proprietary and dependent on the specific requirements of the memory application. For example, one generally chooses from the requirements of power consumption, speed of reading, speed of writing, density of information stored, and cost of fabrication. Each application dictates the preferred approach.

An entirely different approach of obtaining nonvolatile magnetic memory, which exploits another manifestation of spin-polarized transport, is being pioneered by IBM (7) and uses spin-polarized tunneling. Spin-polarized tunneling was first reported in 1975 (8) as a low-temperature effect in which Ge formed the tunneling barrier. The technique was unused until the early 1990s, when spin-polarized tunneling through an alumina barrier

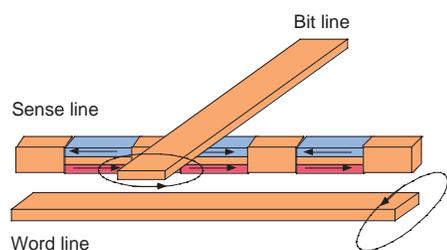


Fig. 5. A schematic representation of RAM that is constructed of GMR elements connected in series. The elements are manipulated for writing or reading by applying magnetic fields that are generated by currents passing through lines above and below the elements.

was reported at room temperature (9); the device concept is illustrated in Fig. 6. As in any tunneling device, two conducting layers are separated by a very thin insulating layer. Upon applying a voltage, however, the potential energy of the acceptor layer is lowered, and the electron can quantum mechanically "tunnel" through the barrier. The tunneling probability increases linearly as the voltage is increased, as in any tunneling device in which normal metals are used as contacts.

However, if the two conductors are ferromagnetic, the same issues that were associated with the GMR effect also arise, namely, the spin description of the states that are available for tunneling. Effectively, an additional barrier is introduced that is spin-dependent, so that, when the two ferromagnetic layers are magnetically aligned, there is a lower impedance than when they are antialigned. A detailed physical understanding of this phenomenon is still being actively researched, but the large changes in device impedance ($\sim 30\%$) at room temperature already permit application for device technology. The operational modes are similar to the spin valve, with one magnetically hard layer and one soft layer. However, the tunneling devices generally carry much lower currents than the all-metal GMR devices, which may be an advantage for portable devices that have limited power. However, the high impedance of a tunneling device may prove to be unattractive in terms of response time or noise. This challenge increases as device sizes are reduced, because the tunneling devices carry their current perpendicular to the plane of the films and, as the area of the device shrinks, the resistance increases.

Nevertheless, considerable progress has been made in demonstrating a memory array architecture that uses spin-polarized tunneling junctions. An example of this application is shown in Fig. 7. The high impedance of tunnel junctions precludes the sense-line

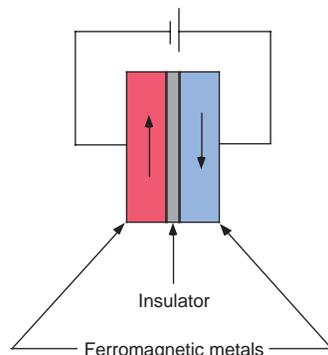


Fig. 6. A magnetic tunnel junction formed by a thin insulating barrier separating two ferromagnetic metal films. Current passing through the junction encounters higher resistance when the magnetic moments are antialigned and lower resistance when they are aligned.

scheme used for GMR devices. Instead, an xy intersecting grid array is used with a tunnel junction that is located at every point of intersection. This approach provides essentially a four-point probe arrangement (two that provide current and two that permit an independent voltage measurement) that is attached to every device. Furthermore, the leads can provide a dual service, because pulse currents, which are directed to run above and below rather than through the device, can provide the necessary magnetic fields to manipulate the magnetization directions in the ferromagnetic layers. This configuration is similar to the addressing scheme of the GMR-based memory. However, one problem is that such an array is multiply shorted through the elements; that is, the electrical path from an input lead to an output lead can proceed through many elements, not just the one at the intersection. The solution to this old problem with grid arrays is to place a diode at every intersection so that the current can pass in only one direction, which eliminates alternative paths. It is a technological challenge to fabricate these diodes in an integrated manner with the tunnel junction storage elements, but its solution could permit the construction of extremely high density memory.

Future Applications

In addition to these applications, which are either already available or near-term, there have been several demonstrations of effects that suggest possible applications. These demonstrations include the injection of spin-polarized carriers into a superconducting strip from a ferromagnetic contact pad, which locally quenches the superconductivity at the point of injection (10). Also, a metal-base transistor has been fabricated, which uses a GMR multilayered magnetic metal film for the base (11). The mean free path of the electrons in the metal base can be altered by switching the GMR layer from its aligned low-resistance state to its antialigned high-resistance state, resulting in a drop in the transconductance of the device. Finally, several research groups are pursuing the injection of spin-polarized carriers into a two-

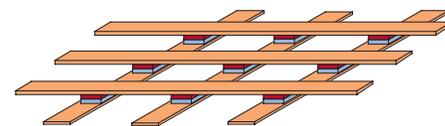


Fig. 7. A schematic representation of RAM that is constructed of magnetic tunnel junctions connected together in a point contact array. The conducting wires provide current to the junctions and permit voltage measurements to be made. They also enable the manipulation of the magnetization of the elements by carrying currents both above and below the magnetic junctions to create magnetic fields.

dimensional electron gas channel that is formed at a compound semiconductor heterostructure interface (12). The long mean free path of electrons in these channels is expected to yield micrometer-length paths that are free of spin-flip scattering for spin-polarized carriers.

The exploitation of spin polarization of carriers represents not only a departure for the field of magnetism and magnetic materials but also a new direction for the field of electronics. The ability to make increasingly smaller electronic devices and the ability to combine dissimilar materials within a device both serve to make spin-polarized effects more important. If the development of useful materials exhibiting 100% polarization succeeds, many of today's digital electronic devices could be replaced with much smaller, more rugged devices that have the added

benefit of possessing intrinsic memory. This is because 100% polarization permits true on/off operation, with an essentially infinite ratio of impedance between the two states, as is found in semiconductor transistors. For example, nonvolatile reprogrammable logic, including the whole array of AND, OR, NAND, and NOR gates, could be fabricated with magnetoelectronic elements. These elements could "remember" their function indefinitely (even when unpowered) but could also be reset with the use of software to serve other functions. Thus, a microprocessor chip could be reprogrammed in midcalculation to reconfigure itself at nanosecond speeds merely by reversing the magnetization of some of its elements in order to most efficiently address the next part of the calculation. This would allow an entirely new approach to computing, which is software-driven rather

than hardware-determined, and a standardized reprogrammable logic chip would become a universal microprocessor.

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