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Magnetoelectronics applications

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Abstract

The introduction of magnetic elements into electronic devices, often referred to as *magnetoelectronics*, is beginning to be seen in both commercial products as well as purely research devices. In this article a brief survey is presented of these applications, with an identification of the operative physical properties involved in their operation. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Magnetoelectronics is a recently emerged field that combines small scale magnetic elements with conventional semiconductor electronics, to obtain devices with new or enhanced functionality. In this brief review, examples will be provided of applications that are already commercially available, those which are under development for near-term production and those which are still in the research stage. An attempt will be made to identify the physical properties which play a determining role in a particular application.

The emergence of this field, as is a common experience in all of the solid state physics, has stemmed from the discovery and development of new materials. And, although there have been many provocative and stimulating ideas, as well as experiments, in spin-polarized transport over the past 30 years [1], it is fair to say that the most important impetus to the field was the discovery of giant magneto-resistance (GMR) in 1988 [2]. Since that discovery of the GMR effect in metal multilayers, in which the current was carried in the plane of the layers (CIP), GMR has also been observed when the current is carried perpendicular to the plane of the layers (CPP) [3]. It has also been studied when the magnetic metal elements are particles entrained in a nonmagnetic metal host (granular GMR) [4,29].

A more recent development is room temperature spin dependent tunneling (SDT) in which two ferromagnetic metal films are separated by an insulating tunneling barrier. Although low temperature studies of spin-dependent tunneling were reported as early as 1972 [5] for Ni particles in Al_2O_3, electronic applications were stimulated by the work published in 1995 [6], on thin film structures.

Another class of material, which has received wide spread interest in the solid state physics community, is the rare earth manganites which can

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exhibit several orders-of-magnitude change in resistance in applied fields. They have been dubbed colossal magnetoresistance (CMR) materials. Although these materials have provided rich ground for studying the complicated physics phenomena exhibited, it is unlikely that they will play any important role in electronic applications in the foreseeable future. Their lack of easy compatibility with semiconductor materials and processing, as well as their intrinsic temperature dependence, make them unattractive for integration into present day electronics.

There are other articles in the present volume dealing with both the physics and the materials science of GMR, SDT and CMR, and no attempt will be made here to repeat those reviews. Also, technology which is described in depth elsewhere in this volume will be mentioned here only for completeness in seeing it in relation to other applications.

2. Application to sensors

The first large-scale commercial application of GMR has been as magnetic field sensors in the read heads of magnetic recording discs for computer information storage. This is a significant, but incremental improvement in a well-established technology that had used inductive pick-up heads for many years to measure the local magnetic fields emanating from recording media. As recently as 1994, the inductive heads were replaced with thin film heads that exploited the anisotropic magnetoresistance (AMR) response in films of permalloy. Although the AMR effect is only $\approx 2\%$ in permalloy, these heads were a considerable improvement in size, weight and cost. They also eliminated the dependence upon disc (or tape) velocity, which characterized an inductive $\mathrm{d}\phi/\mathrm{d}t$ device. Finally, there was an improvement in spatial resolution, since a thin film sensor is used on-edge. This is illustrated in Fig. 1, which describes a GMR thin-film head and makes clear how the discovery of GMR permitted a direct replacement for the earlier AMR application.

The information is stored as magnetic domains along tracks in the recording media. Where two of these oppositely magnetized domains meet, there exists a domain wall, which is a microscopic region of 100–1000 Å (depending upon the material used in the media). While there is no magnetic field emanating from the interior of a magnetized domain itself, in the vicinity of the domain walls there exist uncompensated magnetic poles which do generate magnetic fields which extend out of the media. It is these fields which are sensed by the GMR element. Where the 'heads' of two domains meet there are uncompensated positive poles which generate a magnetic field directed out of the media, and where the 'tails' of two domains meet the walls contain uncompensated negative poles which generate a sink for magnetic lines of flux returning back into the media. The element is fabricated so that the magnetic moment in the easy 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 whenever the head passes over a positive domain wall the magnetic field pushes the easy magnetic moment up and passing over a negative domain wall it is pulled down. The measured resistance of the GMR element thus increases (for more anti-aligned) or decreases (for more aligned). 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 1%/Oe changes in resistance are reported [7].

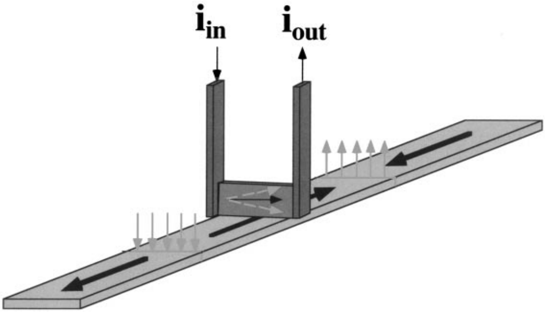

Fig. 1. Schematic representation of a GMR read head passing over recording media containing magnetized regions. The magnetization direction of the soft layer in the head responds to the fields emanating from the media by rotating either up or down. The resulting change in the resistance is sensed by the current passing through the GMR element.

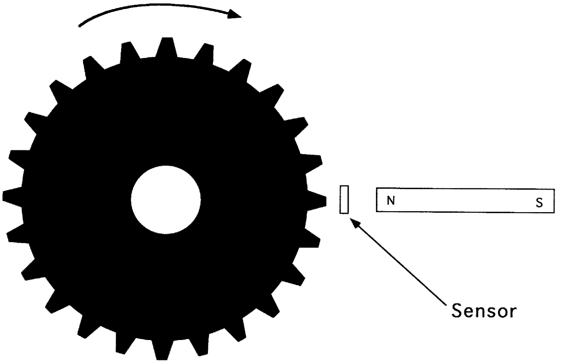

Fig. 2. Typical arrangement for monitoring the rotation of ferrous gear by sensing change in magnetic field from permanent magnet at the sensor location caused by flux closure by gear tooth.

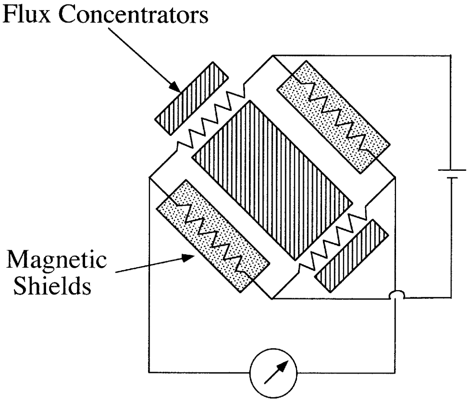

Fig. 3. Typical bridge arrangement for magnetoresistive sensors using flux concentrators and magnetic shields to maximize signal.

The same general concept as that employed in a disc-drive read head can be utilized anywhere magnetic fields can be generated in order to monitor some other function. This occurs naturally, for example to monitor current in an electrical conductor. Either in high power applications or to monitor current in integrated circuits, one need to only orient a thin film GMR element such that the magnetic field generated by the current lies in the plane of the element. Then, as described earlier for the read head, small variations in the current to be monitored will result in variations in resistance in the GMR element. For example at a distance of 1 μm from a wire carrying 1 mA current there is a 2 Oe field, easily sensed by a GMR element.

Magnetic fields may also be generated in many mechanical applications in order to monitor machinery operation. As illustrated in Fig. 2, if one has a ferrous gear, it can be arranged to perturb the distribution of a magnetic fringing field from a permanent magnet located in close proximity. A GMR thin-film sensor can then be located as shown, to be sensitive to the changing orientation of flux every time a gear tooth passes by the magnet. This is an arrangement used to monitor the engine speed in an automobile [8].

Many sensor applications using GMR elements share common design issues, which must be addressed. These are illustrated in Fig. 3. Since the GMR effect exhibits a temperature dependence, in many applications this must be compensated for. The temperature dependence in $\Delta R/R$ arises almost entirely from the simple temperature dependence in the metallic resistance R, and is linear over a large range. To correct for this, one may construct a bridge circuit as shown (all on the small sensor chip by lithographic processing). Thermal variations in R, will to first order, cancel out. One can then magnetically shield two of the bridge elements. This is accomplished by overcoating those elements with a high permeability material, like permalloy. Finally, to enhance the sensitivity of the remaining exposed elements, flux concentrators are introduced to increase the strength of the field to be measured in the vicinity of those elements. These are also lithographically fabricated on the circuit chip from high permeability material. The first commercially available general purpose sensor, incorporating all of these ideas was introduced in 1994 [9].

An entirely different approach to a mechanical sensor was introduced in 1997 [10]. This sensor exploits the fact that a domain wall, within the sensor element itself, can be manipulated in a very controlled manner to measure displacement. Illustrated in Fig. 4 is a spin valve device with the lower GMR layer strongly pinned by an antiferromagnetic layer beneath it. The axis of magnetization is transverse to the long axis of the sensor. The easy

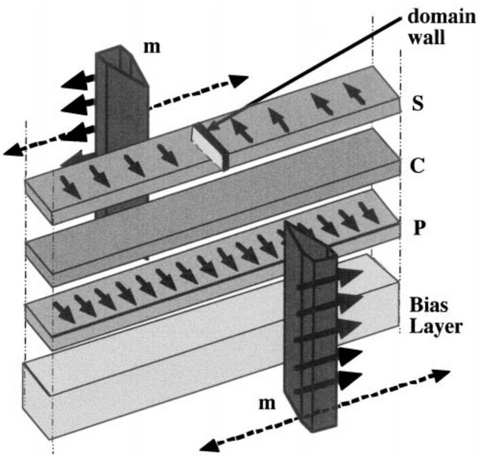

Fig. 4. Exploded view of linear displacement sensor: (s) the switching layer; (c) nonmagnetic conducting spacer; (p) pinned layer; and exchange biasing layer. The magnetization of the various layers and the moments of the indexing magnets (m) are indicated by solid arrows. The dashed arrows indicate the allowed motion of the indexing magnets.

axis of the soft upper layer is similarly transverse to the long axis of the sensor. As in any GMR spin valve, when the magnetization of the pinned and soft layers are aligned, the device has minimum resistance. When they are anti-aligned (by reversing the magnetization of the soft upper layer) it has a maximum resistance. A controllable domain wall is introduced into the soft layer that divides the strip into a low resistance aligned region and a high resistance anti-aligned region. This is done by locating the GMR sensor strip between the poles of a pair of indexing magnets as shown. The indexing magnets create a field which has circulation about a line singularity which connects the sharp-tips of the two indexing magnets. The line singularity defines the domain wall in the soft layer only, and separates the two magnetized regions on either side of it. They are both transverse to the long axis of the strip, but oriented in opposite directions. Merely by sliding the indexing magnets to one end of the strip or the other, when can force the spin valve to be totally aligned (low resistance) or totally anti-aligned (high resistance). The variation between these two states is precisely linearly dependent upon the position of the indexing magnets. These devices can be lithographically fabricated to a length only limited by the substrate wafer size. The reported resolution of 1μm is limited by the domain wall roughness, and the accuracy is limited by the 0.3%/°C temperature dependence of the GMR ratio. With proper attention to these issues, one can obtain a high resolution absolute linear displacement sensor with direct electrical readout and memory retention of its location even when unpowered.

A common problem in many electronics applications is the transfer of low-level high frequency signals from one device to another without picking up additional noise signals. This is generally accomplished with the use of optical isolators, which transform the signal into the modulation of an optical signal. This is then transmitted to an optical detector that returns it into an electrical signal. The optical radiation field is effectively used as the coupling mechanism to avoid direct electrical connection between the two devices. One can now accomplish the same result, more cheaply, by using a magnetic field as the coupling mechanism. The original signal is coupled to a high frequency inductor and the magnetic fields generated are sensed by a GMR element that acts as the input to the second device. These GMR isolators are now commercially available to operate at signal frequencies up to 200 Hz, and should not be fundamentally limited up to 1 GHz [11].

The final example of a magnetoelectronic sensor is the recent development for the detection of magnetically tagged biological specimens [12]. Magnetic particles can be used for biological tagging by coating them with a suitable antibody that will only bind to specific analyte (virus, bacteria, etc.). One can then test for the presence of that analyte, by mixing the test solution with the taggant. This prepared solution is then spread over an integrated circuit chip containing an array of GMR sensor elements. The sensor elements themselves have been individually coated with the specific antibody of interest. Any of the analyte in the solution will bind to the sensor and carry with it the magnetic tag whose magnetic fringing field will act upon the GMR sensor and alter its resistance. By electrically monitoring an array of these chemically coated GMR sensors, one directly obtains a statistical assay of the concentration of the analyte in the test solution.

3. Nonvolatile memory

The next most imminent application to have a large economic impact is nonvolatile memory. ‘Nonvolatile’ means information storage which does not ‘evaporate’ when power is removed from a system. The most widespread nonvolatile information storage is of course magnetic disks and tapes. This is because of their long storage lifetime, low cost and lack of any wear-out mechanism. Computer core memory itself used to be nonvolatile before the introduction of semiconductor random access memory (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 threaded with fine copper wires. Current pulses through the wires could magnetize the cores either right-handedly or left-handedly to store a ‘0’ or a ‘1’. Each core was a bit. The information was read out by current pulses, which could test the core’s direction of magnetization via an inductively induced pulse in another wire. Although this memory was slow, expensive and 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, all of the stored information remained intact.

Honeywell Corporation has recently demonstrated [13] that GMR elements can be fabricated in arrays using standard lithographic processes to obtain memory, which has the speed and density approaching that of semiconductor memory, but is nonvolatile. The structure of such an array is illustrated in Fig. 5. The GMR elements are essentially spin-valve structures as discussed earlier for ferromagnetic field sensors. They are arranged in series connected by lithographic ‘wires’, to form a ‘sense line’. The sense line stores the information and has a resistance, which is the sum of the resistance of all 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. 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 x–y 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 fields, which can act on the magnetic elements. A typical addressing scheme employs pulses in the overlay and underlay lines (typically called word lines and bit lines) which 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 x–y grid overlap however, the two half-select pulses can generate a combined field, which is sufficient to selectively reverse a soft layer, or at higher current levels, sufficient to reverse a hard layer also. Typically one pulse rotates it 90°, and the second pulse completes the task by rotating it the remaining 90°. Through this x–y grid, one can thus address any element of an array to either store information or interrogate the element.

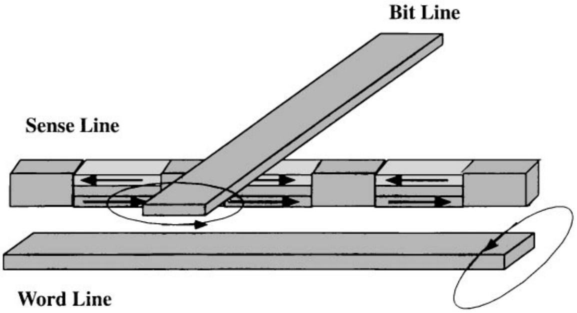

Fig. 5. Schematic representation of random access memory (RAM) constructed of GMR elements connected in series. They are manipulated, for writing or reading, by applying magnetic fields generated by currents passing through lines above and below the elements.

The exact information storage and addressing schemes may be highly varied. One may store information in the soft layer and use ‘destroy’ and ‘restore’ procedures for interrogation. Alternatively, one could construct the individual GMR elements such 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 needing to destroy and restore the information. There are many additional variations on these schemes and the exact scheme employed is often proprietary and depends upon the specific requirements of the memory application. For example one must generally choose among power consumption, speed of reading, speed of writing, density of information stored and cost of fabrication. Each application will dictate the preferred approach.

There is an entirely different approach to obtain nonvolatile magnetic memory by exploiting another manifestation of spin-polarized transport. This approach is being pioneered by IBM Corporation, and utilizes spin-polarized tunneling [14]. The device concept is illustrated in Fig. 6. As in any tunneling device, one has two conducting layers separated by a very thin insulating layer which acts as a barrier to electrical conduction. With the application of a voltage, however, the potential energy of the acceptor layer is lowered and the electron can quantum-mechanically 'tunnel' through the barrier. One expects the tunneling probability to increase linearly as the voltage is increased, as in any tunneling device. However, if the two conductors are ferromagnetic, all of the same issues discussed earlier for the GMR effect also come into play, namely the spin description of the states available for tunneling. Effectively, an additional barrier is introduced which is spin dependent, such that when the two ferromagnetic layers are magnetically aligned there is a lower impedance than when they are anti-aligned. It is still an area of active research to generate a detailed physical understanding of this phenomenon, but the large changes in device impedance ($\approx 30\%$) at room temperature, already permit application for device technology. The operational modes are similar to the spin-valve discussed earlier, with one magnetically stiff layer and one soft layer. However, the tunneling devices generally carry much lower currents than the all-metal GMR devices and this may be an advantage for portable devices where power is limited. On the other hand, the high reported area resistivity of tunneling devices, at $10^6\ \Omega\ \mu\mathrm{m}^2$ [15], may prove unattractive in terms of response time or noise. This is especially challenging as device sizes are reduced, since the tunneling devices carry their current perpendicular to the plane of the films and as the area of the device shrinks, the resistance increases.

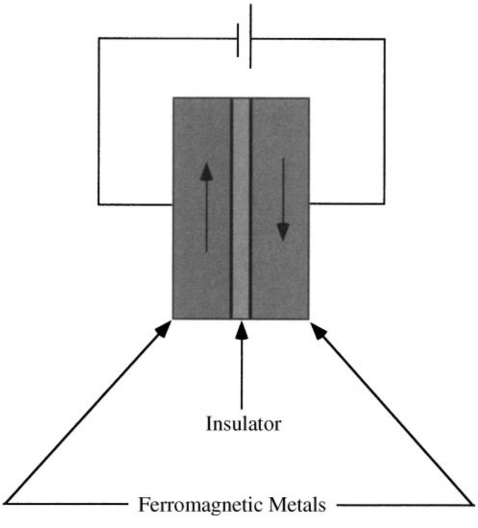

Fig. 6. Magnetic tunnel junction formed by a thin insulating barrier separating two ferromagnetic metal films. Current passing through the junction encounters higher resistance when the magnetic moments are anti-aligned and lower resistance when they are aligned.

Nevertheless, considerable progress has been made in demonstrating a memory array architecture employing spin-polarized tunneling junctions. An example of this application is shown in Fig. 7. The high impedance of tunnel junctions precludes using the sense line scheme employed for GMR devices. Instead, an x–y intersecting grid array is employed with a tunnel junction located at every point of intersection. This provides one with essentially a four-point probe arrangement attached to every device, two of which provide current and the other two permit an independent voltage measurement. Furthermore the leads can provide double service, since 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 is similar to the addressing scheme discussed previously for the GMR-based memory. The one problem, as the perceptive reader might note, 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. This is an old problem with

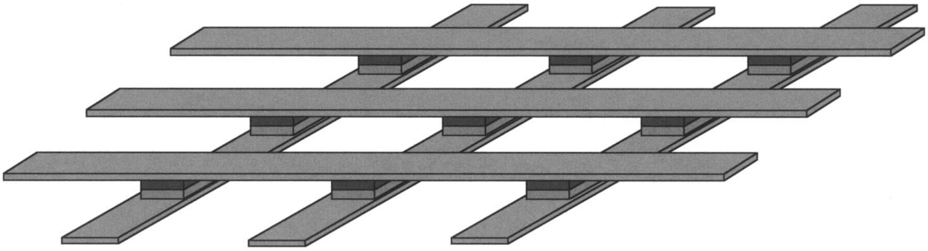

Fig. 7. Schematic representation of random access memory constructed of magnetic tunnel junctions connected together in a point contact array. The conducting wires provide current to the junctions and permit voltage measurements to be made. They also enable manipulation of the magnetization of the elements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

grid arrays and the solution is to place a diode at every intersection so that the current can only pass in one direction. This eliminates the alternative paths. It is a technological challenge to fabricate these diodes in an integrated fashion with the tunnel junction storage elements, but its solution could permit the construction of extremely high-density memory.

4. Hybrid electronic devices

Unlike the applications discussed in Sections 2 and 3, which essentially directly exploit the magneto-transport properties of AMR, GMR or SDT themselves, there are several interesting examples of hybrid devices which combine magnetic elements with superconducting or semiconducting elements to form an intrinsically integrated device. Three of these will be cited: one which exploits the control of the path length for an electron traveling perpendicularly through the layers in a GMR metal multilayer; and two which make use of the local magnetic field emanating from the edges of a magnetic thin film element.

The concept of the metal base transistor was introduced in 1960 [16,30] in an effort to increase the response time over conventional all-semiconductor transistors. Its success depends upon achieving essentially ballistic transport from source to drain through the metallic base layer. Electron transport through a GMR metallic multilayer, if oriented to travel perpendicular to the layers, might be essentially ballistic if the magnetic multilayers were in an aligned state and the multilayer construction was appropriate. It requires very thin layers, defect-free both in their bulk and at their interface, and good electronic band matching for the magnetic and nonmagnetic metals (as is found for BCC Fe/Cr multilayers or FCC Co/Cu multilayers). The first attempt to realize a GMR metal base transistor was reported in 1995 [17], and is illustrated in Fig. 8. The source and drain are both Si, and form Schottky barriers at the metal/semiconductor interface with the GMR metal multilayer base. One anticipates that the shorter electron path length (and higher base resistance) seen when one switches the multilayer from the aligned to the anti-aligned state, will result in a lower drain current. A 215% change in the collector current was indeed observed between the two

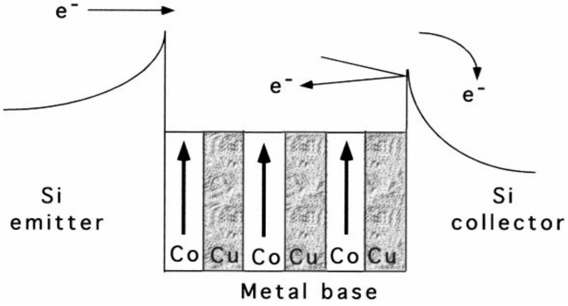

Fig. 8. Schematic energy band diagram of the spin-valve metal base transistor under forward bias. The emitter Schottky barrier is slightly higher than the collector Schottky barrier, reducing quantum mechanical reflections. The magnetic moments of the Co layers are shown in the aligned state, which maximizes the mean free path of the electrons in the base.

configurations, but only 10^{-6} of the emitter current was seen at the collector. More work is needed on this interesting research device.

Although the idea of using the fringing field from small integrated magnetic elements to act upon underlying transport devices was suggested at least a decade ago [18], it is only recently that such devices have been demonstrated. The first of these is a quench switch on a superconducting line [19]. Illustrated in Fig. 9 one sees a ferromagnetic pad covering a section of a superconducting film strip. The pad is electrically insulated from the strip. When the pad is magnetized transverse to the strip axis, the poles at the ends of the pad are well removed from the strip. Any resulting magnetic field is not only weak, but is oriented largely in the plane of the superconducting film and therefore has little effect on the superconducting current. However, when the orientation of the magnetization vector is rotated into alignment with the direction of the superconducting strip, the magnetic field from the poles on the edge of the ferromagnetic pad becomes very strong in the vicinity of the superconductor, is very well localized and is highly oriented to be perpendicular to the plane of the superconducting current. This results in a narrow quenched region across the superconducting strip and a 100% variation in the critical current. Since the orientation of the magnetization in the ferromagnetic pad is easily manipulated by overlay conductor lines, as was discussed in the section on magnetic computer memory, one has a quench switch which is readily controlled by the input of a small electric current (≈1 mA) to rotate the magnetic moment.

This idea of using the fringe fields from a ferromagnetic overlay pad has also been demonstrated on a semiconductor device illustrated in Fig. 10 [20]. The semiconductor device is a Hall cross, a lithographically defined intersection in a high mobility semiconductor epitaxial film. If current is run through one axis of the cross, a voltage is generated across the other two legs whenever a magnetic field is applied perpendicular to the film plane at the intersection of the cross. Since the magnetic fringing field just below the edge of a magnetic pad element is largely perpendicular, it provides an ideal integrated magnetic field source.

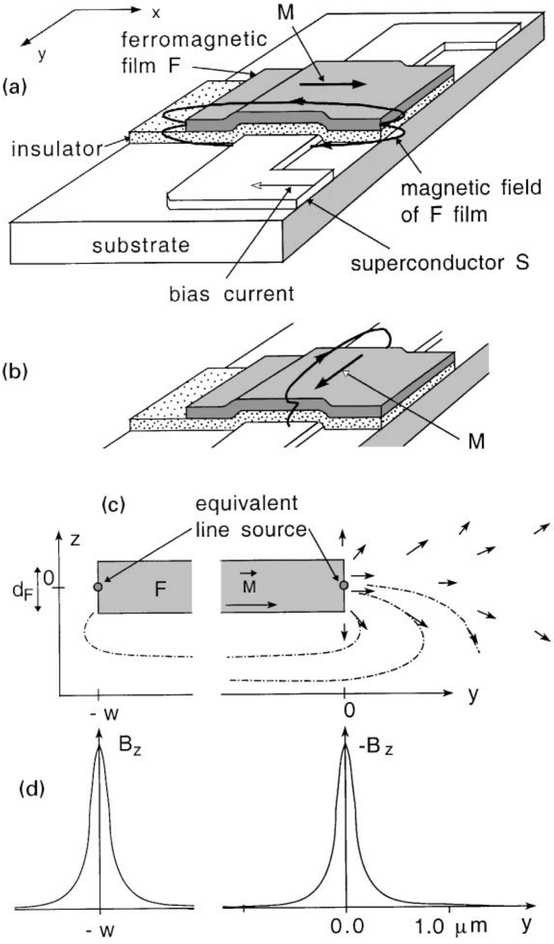

Fig. 9. Prototype device geometry with F film remanent magnetization oriented (a) along x and (b) along y. (c) Cross section of F film showing magnetic fringe field. (d) The profile of B_z beneath the edges of F.

If one reverses the direction of magnetization in the pad, the field polarity is reversed and the sign of the Hall voltage is reversed. Since the magnetization direction is easily reversed using overlay conductor lines, one has here yet another nonvolatile computer memory element, the information being stored in the direction of the magnetization and the readout is provided by the Hall voltage. This device has the advantage of a large resistance change of $\pm 10\,\Omega$, which is well matched to other semiconductor electronics. The technical challenge, as in the other magnetic memory devices, is to properly

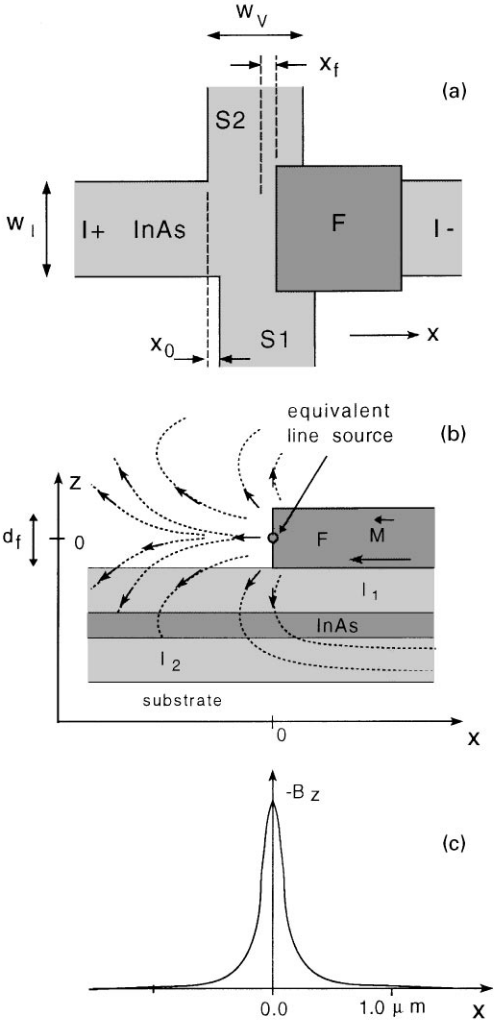

Fig. 10. Schematic diagram of the device geometry. (a) Top view; (b) cross-section view, showing fringe field near the edge of F; and (c) profile of the spatial dependence of the perpendicular component B_z as calculated from a line charge model.

handle the micromagnetic issues in the ferromagnetic pad as the device is reduced to submicron scale.

5. Future directions

While it is difficult to predict the long term future of magnetoelectronic technology or what new scientific discoveries will be facilitated by this research, there are very recent efforts which indicate promising new directions. They all fall broadly into what may be called spin-polarized transport. Of course, the GMR effect itself and spin-polarized tunneling are both samples of spin-polarized transport. However, there are three research areas that are vital to making further progress in spin-polarized transport. Fortunately, there are examples of significant progress in all of them.

First, is the search for 100% spin-polarized materials. It is obvious that increasing the spin-polarization of the carriers in any device will enhance its magnetoelectronic performance. In the best materials, however, this polarization is only partial. For example, the Fe/Cr GMR multilayer system yields 150% ($\Delta R/R$) in the best reported case [21]. This cannot compare to on/off resistance ratios of 10^6 currently obtained in good semiconductor electronic devices. The limitation, of course, is that the important room temperature ferromagnetic metals (Fe, Co and Ni) and their alloys all have a spin-polarization P of the carriers near the Fermi level of $\approx 50\%$. $P = (n_+ - n_-)/(n_+ + n_-)$ and $n_+(n_-)$ are the number of up (down) spins. It is only with 100% polarized materials that one can hope to address some of the most important electronic applications. For example, it has been suggested that spin-polarized devices could form the basis of a reprogrammable logic technology [22]. By setting the magnetization of a set of magnetoresistive elements, one can define their function as an AND, OR, NAND or NOR gate. This function can then be altered, on the fly, by merely resetting the magnetization on the appropriate elements. This is a very powerful concept, since it introduces the ideas of a universal processor which can be reprogrammed by software, in mid-calculation, to be optimized for any particular calculational step. Furthermore, by employing magnetic elements, the devices 'remember' their function even in the absence of any additionally applied power. This ensures retention of the programmed configuration even when the processor is powered off, and no need during operation to consume power merely to retain a programmed configuration. However, logic devices must be capable of very high on/off ratios, since they each must control the power to switch additional devices. This is the well-known 'fan-out' problem. Since present GMR devices can at best change the current flowing through them by a factor of 2, they cannot alone form the basis for a reprogrammable logic technology. They must be supplemented with supporting transistors. While this approach may lead to a useful technology, the discovery of practical 100% polarized materials would significantly enhance its development.

Fortunately, there has recently been developed a remarkable new technique to rapidly determine the degree of spin-polarization of the carriers in a material. It is called spin-polarized Andreev reflection point contact spectroscopy [23]. Using a sharpened tip of a superconducting material in physical contact with the surface of the ferromagnetic metal to be characterized, one merely measures the I–V curve. Plotting $\mathrm{d}I/\mathrm{d}V$ versus V, one obtains a value of zero at $V = 0$ for the case of 100% spin polarization of the carriers at the Fermi surface in the ferromagentic metal. For 0% polarization, as one would obtain in a normal metal such as Cu, Au or Ag, $\mathrm{d}I/\mathrm{d}V = 2$ at $V = 0$. It is an absolute, self-calibrating technique which is independent of carrier density or mobility, and requires no lithographic processing or special barrier fabrication, as has traditionally been done to measure spin polarization by tunneling into superconductors. This technique has been applied to both film and bulk samples and has provided the largest survey of spin polarization values to date. Especially promising are the results for CrO_2 of 90% and $LaSrMnO_3$ of 78%. There have been predictions, largely based upon electronic structure calculations, of several materials which should be 100% spin-polarized. As of yet, none of these predictions have proven to be true under experimental testing. This may be due to shortcomings in the material preparation or inadequacies in the theoretical modeling. It may, in fact, prove to be true that nature will not allow any materials to be 100% spin-polarized, but there is as yet no theoretical basis for this constraint. What we do have is a rapid experimental technique for testing any new material, so that the challenge to find 100% spin-polarized materials provides a goal for both the electronic structure community as well as the magnetic materials community. The potential pay-off for both science and technology is very high.

The second research area, which provides serious challenges is that of ‘spin injection’. ‘Spin injection’ is the process by which a highly spin-polarized current is transmitted from the ferromagnetic metal into another material such as another metal, a semiconductor or a superconductor, while retaining its spin-polarized character. There are already examples of this. In CPP-GMR measurements, the spin-polarized carriers traverse a series of layers, passing between normal and ferromagnetic metals. From the electronic band structure of these materials has emerged a reasonably clear picture of how this process depends upon the band alignment and hybridization at the interfaces [24]. Less well understood is the transition through a ferromagnetic/superconducting interface that is not confined to ballistic transport, as it is in the Andreev point contract geometry described above. Nevertheless, experiments have been carried out in which carriers, originating from a ferromagnetic contact pad have quenched the transport in a superconducting strip [25]. Fig. 11 shows the result of current injection from a permalloy pad compared with that from a Au pad in quenching the current in a superconducting strip. In both cases, one is presumably upsetting the balance of the Cooper pairs in the superconductor, but the spin-polarized current seems much more effective. A complete theoretical treatment of this process has not yet emerged. It is nevertheless a clear example of the effect of spin injection.

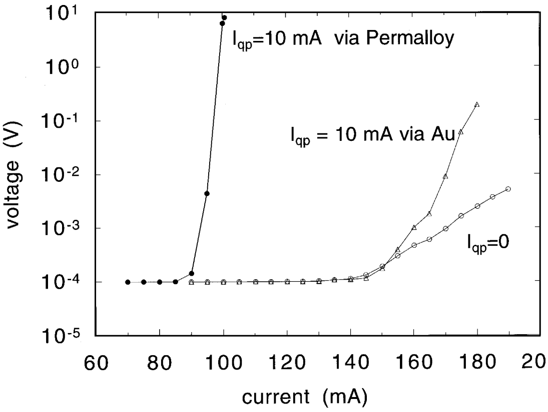

Fig. 11. I–V curve for spin injection from two contracts into YBa_2Cu_3.

The most difficult, and perhaps the most important, case of spin injection is that from a ferromagnet into a semiconductor. Although interesting examples of potential devices have been presented as for back as 1990 [26], and several attempts have been made to realize them, there is as yet no report of successful spin injection into a semiconductor. One of the problems may lie in the fact that the metal/semiconductor interface generally forms a Schottky barrier. Although one might expect this tunneling barrier to be no more destructive to the spin polarization than the insulating barriers used for spin-dependent tunneling studies described earlier, the nature of the electronic states at the metal/semiconductor interface are poorly understood. It is known that the semiconductors themselves are fully capable of carrying highly polarized currents over distances of 100 μm. In a series of important experiments it has been shown that high spin polarizations can be generated in GaAs by polarized optical pumping and that they have long lifetimes [27]. It is now clear that if the physical challenge of injecting spin-polarized carriers electrically into semiconductor devices can be overcome, then the whole panoply of semiconductor quantum devices can be reconsidered to include spin polarized effects. This would provide another dimension to these devices, by removing time reversal symmetry as one might obtain by placing the device in a strong magnetic field. Since the spin system does not couple strongly to the crystal fields, except through the generally weak spin-orbit interaction, on the fast time scales now being approached by modern computers, the spin states could be considered quasi-steady state. This may make them suitable for use as extremely small information storage elements or logic elements. One could envision single spin devices forming the analog to single electron devices currently being explored by the semiconductor community. Indeed, the success of the optical pumping may lead to 'optical spin-injection' devices, which could operate without any electrical connections or in concert with them for reading and writing.

The third area in which work is needed is less-well defined, but more general, since it underlies all understanding of magnetoelectronic applications. This is the development of a general theoretical understanding of spin-polarized transport in solids. Of course, the theory of unpolarized carrier transport is difficult enough, and still far from complete. However, in order to make progress in new materials research, understanding interface issues or truly exploiting the properties of spin-polarized currents, theoretical effort must be directed towards understanding the physics which determines the spin lifetime, the coherence of the spin state and the interactions between the spin current and the micromagnetic configuration of a system, to list just a few examples. Considerable progress, for example, has been made recently in understanding spin-polarized tunneling based upon the actual electronic band structure of the materials involved [28]. This work indicates the kind of detailed theoretical effort needed to make progress in understanding the other problems in spin-polarized transport.

This is obviously a cross-disciplinary field. Workers in magnetism and magnetic materials have generally ignored issues of electronic transport. Similarly, researchers in the fields of superconductivity and semiconductors, intrinsically transport-oriented communities, generally have little understanding of solid state magnetism. In order to truly exploit the opportunities offered by this new field, it will be imperative to form cross-disciplinary research teams. There is evidence of this now occurring in Germany, Japan and the United States. In the end, the future of the field may lie in these efforts.

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References

[1] G.A. Prinz, Phys. Today 48 (1995) 58.
[2] M. Baibich, J. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, J. Chazelas, Phys. Rev. Lett. 61 (1988) 2472.

[3] W.P. Pratt Jr., S.F. Lee, J.M. Slaughter, R. Lolee, P.A. Schroeder, J. Bass, Phys. Rev. Lett. 66 (1991) 3060.

[4] A.E. Berkowiz, J.R. Mitchell, M.J. Carey, A.P. Young, S. Zhang, F.E. Spada, F.T. Parker, A. Hutton, G. Thomas, Phys. Rev. Lett. 68 (1992) 3745.

[5] J.I. Gittleman, Y. Goldstein, S. Bozowski, Phys. Rev. B 5 (1972) 3609.

[6] J. Moodera, L. Kinder, T. Wong, R. Meservey, Phys. Rev. Lett. 74 (1995) 3273.

[7] C. Tang, R. Fontana, T. Lin, D.E. Heim, V.S. Speriosu, B.A. Gurney, M.L. Williams, IEEE Trans. Magn. 30 (1994) 3801.

[8] C. Smith, Proc. UK Conf. for Sensors, Test and Measurement Technology, Birmingham, England, Jan. 22–23, 1997.

[9] J.M. Daughton, J. Brown, E. Chen, R. Beech, A. Pohm, W. Kude, IEEE Trans. Magn. 30 (1994) 4608.

[10] M.M. Miller, G.A. Prinz, P. Lubitz, L. Hoines, J.J. Krebs, S.F. Cheng, F.G. Parsons, J. Appl. Phys. 81 (1997) 4284.

[11] T. Hermann, W. Black, S. Hui, IEEE Trans. Magn. 33 (5) (1997) 4029.

[12] D.R. Baselt, G.U. Lee, M. Natesan, S.W. Metzger, P.E. Sheehan, R.J. Colton, Biosensors Bioelectron. 13 (1998) 731.

[13] M. Dax, Semicond. Int. 20 (10) (1997) 84.

[14] R.E. Scheuerlein, Paper presented at the IEEE Int. Conf. on Nonvolatile Memory Technology, Albuquerque, NM, 22–24 June, 1998.

[15] Y. Lu, X.W. Li, G. Xiao, R.A. Altman, W.J. Gallagher, A. Marley, K. Roche, S. Parkin, J. Appl. Phys. 83 (1998) 6515.

[16] A. Rose, Interim Report No. 6A, RCA, June, 1960.

[17] D.J. Monsma, J.C. Lodder, Th.J.A. Popma, B. Dieny, Phys. Rev. Lett. 74 (1995) 5260.

[18] G.A. Prinz, Science 250 (1990) 1092.

[19] T.W. Clinton, M. Johnson, Appl. Phys. Lett. 70 (1997) 1170.

[20] M. Johnson, B.R. Bennett, M.J. Yang, M.M. Miller, B.V. Shanabrook, Appl. Phys. Lett. 71 (1997) 974.

[21] E.E. Fullerton, M.J. Conover, J.E. Mattson, C.H. Sowers, S.D. Bader, Appl. Phys. Lett. 63 (1993) 1699.

[22] M.M. Hassoun, W.C. Black, E.K.F. Lee, R.L. Geiger, A. Hurst, IEEE Trans. Magn. 33 (1997) 3307.

[23] R.J. Soulen Jr., J.M. Byers, M.S. Osofsky, B. Nadgorny, T. Ambrose, S.F. Cheng, P.R. Broussard, C.T. Tanaka, J. Novak, J.S. Moodera, A. Barry, J.M.D. Coey, Science 282 (1998) 85.

[24] X.-G. Zhang, W.H. Butler, J. Appl. Phys. 81 (1997) 4576.

[25] D.B. Chrisey, M.S. Osofsky, J.S. Horowitz, R.J. Soulen, B. Woodfield, J. Byers, G.M. Daly, P.C. Dorsey, J.M. Pond, M. Johnson, IEEE Trans. Appl. Supercond. 7 (1997) 2067.

[26] S. Datta, B. Das, Appl. Phys. Lett. 56 (1990) 665.

[27] J.M. Kikkawa, D.D. Awschalom, Nature 397 (1999) 139.

[28] J.M. MacLaren, W.H. Butler, X.-G. Zhang, J. Appl. Phys. 83 (1998) 6521.

[29] J.Q. Xiao, J.S. Jiang, C.L. Chien, Phys. Rev. Lett. 68 (1992) 3749.

[30] M.M. Atalla, D. Kahng, IRE Trans. Electron Dev. 9 (1962) 507.