International Journal of Advanced Engineering Technology E-ISSN 0976-3945

Research Article

GIANT MAGNETO RESISTANCE

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Magneto resistance

Magneto resistance is the property of a material to change the value of its electrical resistance when an external magnetic field is applied to it. The effect was first discovered by William Thomson (aka Lord Kelvin) in 1856, but he was unable to lower the electrical resistance of anything by more than 5%. This effect was later called ordinary Magnetoresistance (OMR). More recent researchers discovered materials showing giant Magnetoresistance (GMR), colossal Magnetoresistance (CMR) and magnetic tunnel effect (TMR). William Thomson (Lord Kelvin) first discovered ordinary Magnetoresistance in 1856. He experimented with pieces of iron and discovered that the resistance increases when the current is in the same direction as the magnetic force and decreases when the current is at 90° to the magnetic force. He then did the same experiment with nickel and found that it was affected in the same way but the magnitude of the effect was greater. This effect is referred to as anisotropic Magnetoresistance (AMR). The phenomenon called Magnetoresistance (MR) is the change of resistance of a conductor when it is placed in an external magnetic field. For ferromagnetism like iron, cobalt and nickel this property will also depend on the direction of the external field relative to the direction of the current through the magnet. Exactly 150 years ago W. Thomson (Lord Kelvin) measured the behavior of the resistance of iron and nickel in the presence of a magnetic field. This difference in resistance between the parallel and perpendicular case is called anisotropic magneto-resistance (AMR). It is now known that this property originates from the electron spin-orbit coupling. In general Magnetoresistance effects are very small, at most of the order of a few per cent. The MR effect has been of substantial importance technologically, especially in connection with read-out heads for magnetic disks and as sensors of magnetic fields. The most useful material has been an alloy between iron and nickel, $Fe_{20}Ni_{80}$ (permalloy). In general, however, there was hardly any improvement of the performance of magnetoresistive materials since the work of Kelvin. The general consensus in the 1980s was that it was not possible to significantly improve on the performance of magnetic sensors based on Magnetoresistance.

Therefore it was a great surprise when in 1988 two research groups independently discovered materials showing a very large Magnetoresistance, now known as giant Magnetoresistance (GMR). These materials are so called magnetic multilayers, where layers of ferromagnetic and non-magnetic metals are stacked on each other. The widths of the individual layers are of nanometer size – i.e. only a few atomic layers thick. In the original experiments leading to the discovery of GMR one group, led by Peter Gruenberg, used a trilayer system Fe/Cr/Fe, while the other group, led by Albert Fert , used multilayer's of the form (Fe/Cr) n where n could be as high as 60.

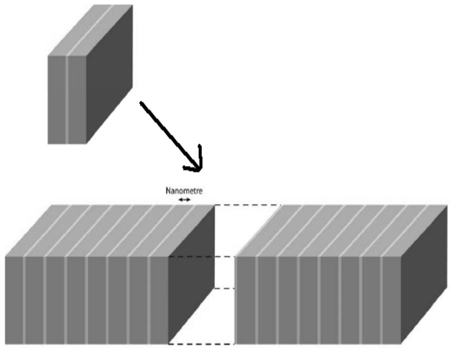

Figure 1. Schematic figure of magnetic multilayer's.

Nanometer thick layers of iron are separated by nanometer thick spacer layers of a second metal (for example chromium or copper). The top figure illustrates the trilayer Fe/Cr/Fe used by Gruenberg's group, and the bottom the multilayer (Fe/Cr)n , with n as high as 60, used by Fret's group. In figure 2 the measurements of Gruenberg's group are displayed (left) together with those of Fret's group (right). The y-axis and x-axis represent the resistance change and external magnetic field, respectively. The experiments show a most significant negative Magnetoresistance for the trilayer as well as the multilayer's. The systems to the right, involving large stacks of layers, show a decrease of resistance by almost 50% when subjected to a magnetic field. The effect is much smaller for the system to the left, not only because the system is merely a trilayer but also because the experiments led by Gruenberg were made at room temperature, while the experiments reported by Fert and co-workers were per-formed at very low temperature (4.2K).

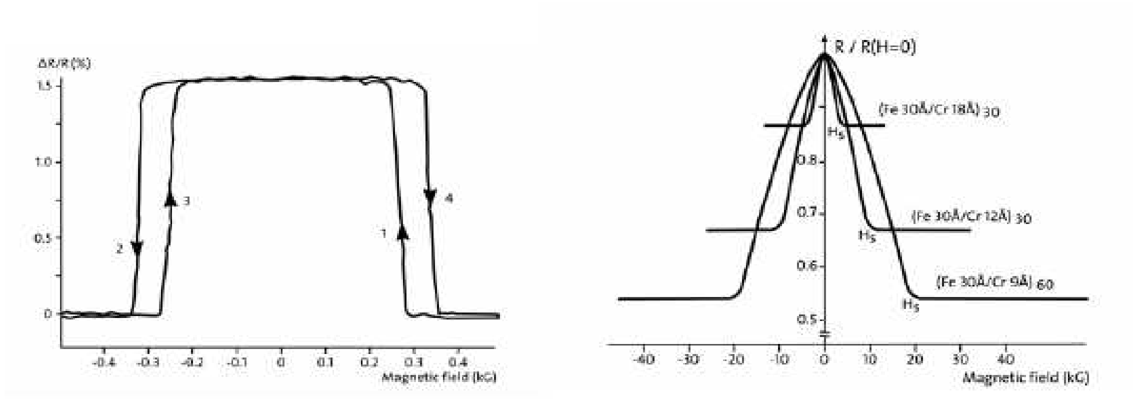

Figure 2: Left: Magnetoresistance measurements at room temperature for the trilayer system Fe/Cr/Fe.

To the far right as well as to the far left the magnetizations of the two iron layers are both parallel to the external magnetic field. In the intermediate re-goon the magnetizations of the two iron layers are antiparallel. The experiments also show a hysterisis behaviour (difference 1 and 4 (2 and 3)) typical for magnetization measurements.

Right: Magnetoresistance measurements (4.2K) for the multilayer system (Fe/Cr)n . To the far right (>HS , where HS is the saturation field) as well as to the far left (< – HS) the magnetizations of all iron layers are parallel to the external mag-netic field. In the low field region every second iron layer is magnetized antiparallel to the external magnetic field. 10 kG = 1 Tesla.

Grünberg also reported low temperature magnetoresistance measurements for a system with three iron layers separated by two chromium layers and found a resistance decrease of 10%.

Not only did Fert and Grünberg measure strongly enhanced magnetoresistivities, but they also identi-fied these observations as a new phenomenon, where the origin of the magnetoresistance was of a to-tally new type. The title of the original paper from Fert´s group already referred to the observed effect as Giant Magnetoresistance. Grünberg also realized at once the new possibilities for technical applications and patented the discovery. From this very moment the area of thin film magnetism research completely changed direction into magnetoelectronics.

The discovery of giant magnetoresistance immediately opened the door to a wealth of new scientific and technological possibilities, including a tremendous influence on the technique of data storage and magnetic sensors. Thousands of scientists all around the world are today working on magnetoelectronic phenomena and their exploration. The story of the GMR effect is a very good demonstration of how a totally unexpected scientific discovery can give rise to completely new technologies and commercial products.

Giant magneto resistance

Giant magnetoresistance (GMR) is a quantum mechanical magnetoresistance effect observed in thin film structures composed of alternating ferromagnetic and non magnetic layers. The 2007 Nobel Prize in physics was awarded to Albert Fert and Peter Grünberg for the discovery of GMR.

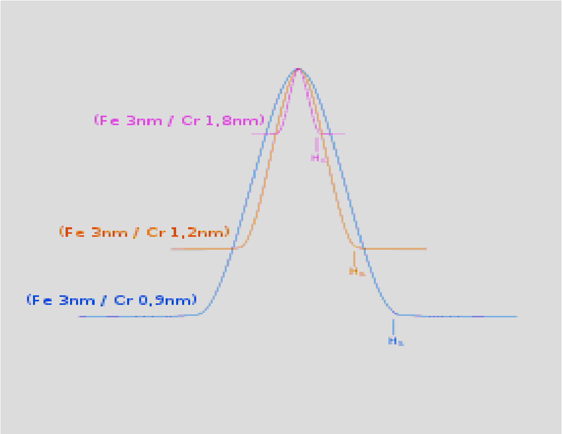

Figure 3 : The effect of GMR

The effect is observed as a significant change in the electrical resistance depending on whether the magnetization of adjacent ferromagnetic layers are in a parallel or an antiparallel alignment. The overall resistance is relatively low for parallel alignment and relatively high for antiparallel alignment. GMR is used commercially by hard disk drive manufacturers.

Discovery

GMR was first discovered in 1988, in Fe/Cr/Fe trilayers by a research team led by Peter Grünberg of Forschungszentrum Jülich (DE), who owns the patent. It was also simultaneously but independently discovered in Fe/Cr multilayers by the group of Albert Fert of the University of Paris-Sud (FR). The Fert group first saw the large effect in multilayers that led to its naming, and first correctly explained the underlying physics. The discovery of GMR is considered the birth of spintronics. Grünberg and Fert have received a number of prestigious prizes and awards for their discovery and contributions to the field of spintronics including the 2007 Nobel Prize in Physics.

The resistance of a GMR device can be understood from the following somewhat simplified picture. In figure 4 a plot of the magnetic configuration for the

FM/ NM/ FM (ferromagnetic/non-magnetic/ ferromagnetic) multilayer is made together with the corresponding electron density of state for the two ferromagnetic sides (FM). In the absence of a magnetic field (at the top) the two FM layers are separated from each other in such a way that they have opposite magnetization directions. In the presence of a magnetic field the magnetizations of the two FM layers will be parallel (at the bottom). An electrical current is now sent through the system for both configurations. As already mentioned above the current through the FM layer is composed of two types – one spin up current and one spin down current – and the resistance for these two currents will differ. When an electron leaves the first iron layer and enters the non-magnetic metal there will be additional scattering processes giving rise to extra resistance. Since the spin up and spin down particles have different density of states at the Fermi level or rather, they originate from energy levels having different character; the resistance not only within the FM layers, but also that originating from the FM/NM interface will be different for the two spins. Inside the NM layer the up and down spins will experience the same resistance, but generally this is low compared to those in the FM layers and FM/NM interfaces and can here be neglected.

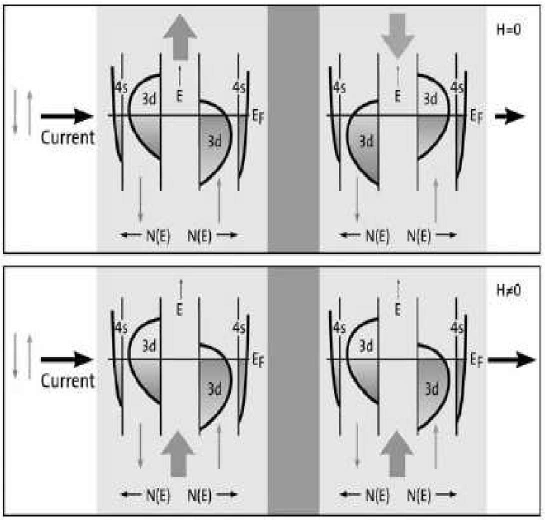

Figure 4 Schematic illustration of the electronic structure of a trilayer system with two ferromagnetic layers on both sides separated by nonmagnetic material. The top figure is for the case without external magnetic field (H=0), i.e. when the two magnetic layers have opposite magnetizations (indicated by the thick blue and orange arrows at the top of the topmost figure). The bottom figure is for the case when an external mag-netic field (H ≠ 0) has forced the two magnetizations to be parallel (two thick blue arrows at the bottom of the lower figure.).The magnitude of the four magnetizations is the same. When the electrons enter the second iron layer they will again experience spin dependent scattering at the NM/FM interface. Finally the spin up and spin down electrons go through the second iron layer with the same resistance as in the first iron layer, which still of course differs for the two spins. For simplicity the resistance for the spin up (down) electrons through the FM layer and the scattering at the interface to the NM layer will be called R↑ (R↓). Thus when the two layers have parallel spin polarizations (magnetizations), i.e. in the presence of an external magnetic field (H), the resistance for the spin up channel is 2 R↑ and for the spin down channel it is 2 R↓. Standard addition of resistances for a parallel current configuration gives the following total resistance, RH, in the presence of an external magnetic field; RH = 2R↑R↓/(R↑ + R↓).

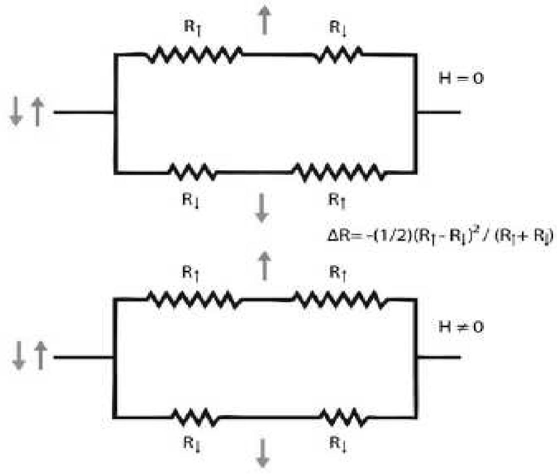

Figure 5. The same physical system as in figure 4. The magnetic layers are now represented by resistances R↑ and R↓. This shows very clearly that the total resistance for the two cases are different, i.e. there is a magnetoresistance effect. In case R↑ >> R↓ it is practically only the lowest of the four possibilities which will permit a current. In the lower picture with parallel magnetizations the resistance for the spin up (spin down) electrons will be R↑ (R↓) in both magnetic layers. In the upper picture with antiparallel magnetizations the spin up (spin down) electrons will have a resistance R↑ (R↓) in the first magnetic layer to the left. In the second magnetic layer the resistance for the spin up (spin down) electron will be R↓ (R↑), since the magnetization environment has here become totally opposite compared to the first magnetic layer.

In the case of no external magnetic field, (H=0), the configuration between the two magnetic layers is antiparallel. In this case the first scatterings in the left part of the multilayer system are exactly the same as before for the lower part of the figure. However, when a spin up electron enters into the second FM layer it finds itself in a totally upside-down situation where the conditions are now exactly the same as they were for the spin down electron in the initial FM layer. Thus the spin up particle will now experience a total resistance of R↑

+ R↓. The spin down particle will be affected in the same but opposite way and its resistance will be R↓ + R↑. The total resistance will accordingly be R0 = (1/2)(R↑+R↓). Thus the difference in resistance between the two cases (magnetic field or not) becomes:

$\Delta R = RH - R0 = -(1/2)(R\uparrow - R\downarrow)2 /(R\uparrow + R\downarrow)$.

Thus the larger the difference between R↑ and R↓ the larger the negative magnetoresistance. This expression clearly shows that the magnetoresistance effect arises from the difference between the resistance behaviors of the spin up and down electrons.

Types of GMR

Multilayer GMR

In multilayer GMR two or more ferromagnetic layers are separated by a very thin (about 1 nm) non-ferromagnetic spacer (e.g. Fe/Cr/Fe). At certain thicknesses the RKKY coupling between adjacent ferromagnetic layers becomes antiferromagnetic, making it energetically preferable for the magnetizations of adjacent layers to align in anti-parallel. The electrical resistance of the device is normally higher in the anti-parallel case and the difference can reach more than 10% at room temperature. The interlayer spacing in these devices typically corresponds to the second antiferromagnetic peak in the AFM-FM oscillation in the RKKY coupling.

The GMR effect was first observed in the multilayer configuration, with much early research into GMR focusing on multilayer stacks of 10 or more layers.

Spin valve GMR

An antiparallel configuration is shown on the right and a parallel configuration on the left. FM stands for ferromagnetic, NM for non ferromagnetic, ↑ is a spin up electron and ↓ is a spin down electron. The vertical black arrows in the FM layers show the direction of the magnetisation. The arrows across the spin valves show the electron path. A bend in the path shows that an electron was scattered.

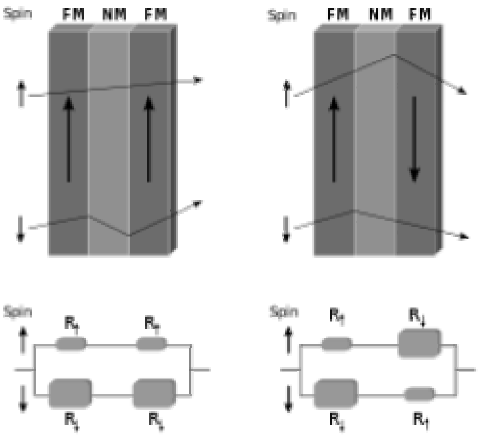

Figure 6: Spin-valve GMR.

Research to improve spin valves is focused on increasing the magnetoresistance ratio by practical methods such as increasing the resistance between individual layers interfacial resistance, or by inserting half metallic layers into the spin valve stack. These work by increasing the distances over which an electron will retain its spin (the spin relaxation length), and by enhancing the polarization effect on electrons by the ferromagnetic layers and the interface. At the National University of Singapore, S. Bala Kumar and collaborators experimented with the interfacial resistance principle to show the magnetoresistance is suppressed to zero in NiFe/Cu/NiFe spin-valve at high amounts of interfacial resistance.

A high performance from the spin valve is achieved using a large GMR. The GMR ratio is maximised by finding the optimal resistance and polarization of the interface between layers.

Spacer materials include Cu (copper), and ferromagnetic layers use NiFe (permalloy), which are both widely studied and meet industrial requirements.

Pseudo-spin valve

Pseudo-spin valve devices are very similar to the spin valve structures. The significant difference is the coercivities of the ferromagnetic layers. In a pseudo-spin valve structure a soft magnet will be used for one layer; where as a hard ferromagnet will be used for the other. This allows an applied field to flip the magnetization of the hard ferromagnet layer. For pseudo-spin valves, the non-magnetic layer thickness must be great enough so that exchange coupling minimized. This reduces the chance that the alignment of the magnetisation of adjacent layers will spontaneously change at a later time.

Granular GMR

Granular GMR is an effect that occurs in solid precipitates of a magnetic material in a non-magnetic matrix. To date, granular GMR has only been observed in matrices of copper containing cobalt granules. The reason for this is that copper and cobalt are immiscible, and so it is possible to create the solid precipitate by rapidly cooling a molten mixture of copper and cobalt. Granule sizes vary depending on the cooling rate and amount of subsequent annealing. Granular GMR materials have not been able to produce the high GMR ratios found in the multilayer counterparts.

GMR and Tunnel magnetoresistance (TMR)

Tunnel magnetoresistance (TMR) is an extension of spin valve GMR in which the electrons travel with their spins oriented perpendicularly to the layers across a thin insulating tunnel barrier replacing the non ferromagnetic spacer. This allows a larger impedance, a larger magnetoresistance value (~10x at room temperature) and a ~0 temperature coefficient to be achieved simultaneously. TMR has now replaced GMR in disk drives, in particular for high area densities and perpendicular recording.

TMR has led to the emergence of MRAM memories and reprogrammable magnetic logic devices.

Applications

GMR has triggered the rise of a new field of electronics called spintronics which has been used extensively in the read heads of modern hard drives and magnetic sensors. A hard disk storing binary information can use the difference in resistance between parallel and antiparallel layer alignments as a method of storing 1s and 0s.

A high GMR is preferred for optimal data storage density. Current perpendicular-to-plane (CPP) Spin valve GMR currently yields the highest GMR. Research continues with older current-in-plane configuration and in the tunnelling magnetoresistance (TMR) spin valves which enable disk drive densities exceeding 1 Terabyte per square inch.

Hard disk drive manufacturers have investigated magnetic sensors based on the colossal magnetoresistance effect (CMR) and the giant planar Hall effect. In the lab, such sensors have demonstrated sensitivity which is orders of magnitude stronger than GMR. In principle, this could lead to orders of magnitude improvement in hard drive data density. As of 2003, only GMR has been exploited in commercial disk read-and-write heads because researchers have not demonstrated the CMR or giant planar hall effects at temperatures above 150K.

Magnetocoupler is a device that uses giant magnetoresistance (GMR) to couple two electrical circuits galvanicly isolated and works from AC down to DC.

Vibration measurement in MEMS systems.

Detecting DNA or protein binding to capture molecules in a surface layer by measuring the stray field from superparamagnetic label particles.

Applications of GMR

GMR has been used by development of many applications. A few of them are listed below.

Application to sensors

The first large-scale commercial application of GMR has been as magnetic filed 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 fileds 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 elect is only +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 d//dt 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 GMRpermitted 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, depending upon the material used in the media. While there is no magnetic filed 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 filed 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 filed 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 filed. Typically 1%/Oe changes in resistance are reported

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 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 GMR elements are essentially spin-valve structures as discussed earlier for ferromagnetic filed 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 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 filed 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 X y grid overlap however, the two half-select pulses can generate a combined filed, 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 903, and the second pulse completes the task by rotating it the remaining 903. Through this x X y grid, one can thus address any element of an array to either store information or interrogate the element. 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.

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

CONCLUSION

The proposed study titled “A study of role of GMR development of intelligent memory devices” undertakes to:

1. understand, compare and contras theories of GMR
2. derive usage of GMR in actual world
3. tetris on model application of combined memory-processor module

In general the study aims to generate understanding towards application of GMR in commercial world. It further aims to allow coming up with ideas that support betterment in technology of GMR and to develop methods and devices with reduces strain in the current machines especially various types of Memory Modules and allied technology using GMR.

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