Spintronics

2. Devices and Materials

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In this part, the commercial applications of spintronics are described briefly to indicate the potential of spintronics. This is followed by a description of some of the proposed devices. Some devices have been commercially exploited while others are still in the development stage. A discussion of materials suitable for spintronic devices will be given.

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Introduction

In Part 1 of this serial article we discussed the polarization of electron spin in ferromagnetic materials, polarization injection into a normal metal (or superconductor or semiconductor) from a ferromagnet, and detection of induced polarization. In this part, commercial applications of spintronics will be described followed by a discussion of proposed devices and materials suitable for spintronics.

Commercial Exploitation of Spintronic Devices

When a magnetic field is applied there is a change in resistance (of the order of 1% for 1 Tesla = 10,000 Gauss) even in normal metals. In some ferromagnetic metals the direction of magnetization can be reversed on the application of a magnetic field of the order of 10 Gauss. Using a spin valve device to be described below one can achieve a magneto-resistance of 10% or more with an applied field of about 10 Gauss. This phenomenon called Giant Magneto-resistance (GMR) was discovered in 1988 by Albert Fert in Paris and Peter Grnberg in Julich, in magnetic multilayers in which layers of ferromagnetic materials were separated by thin layers of a normal metal, for example in Co/Cu multilayers. In these materials the magnitude of the magnetoresistance is more than 100% at low temperatures.The French National Centre for Scientific Research (CNRS) has awarded the Medaille dOr (Golden Medal) for 2005 to Prof A Fert. Application of GMR in the read heads of computer discs was developed by IBM in 1997, using thin film techniques. About 615 million such read heads are produced every year. The GMR read heads are able to sense very small magnetic fields in the written information on hard discs. This has led to a substantial decrease in space required to store bits of information and has phenomenally increased the storage capacity of hard discs. Today hard disks have a storage capacity of 200 GB. The market is estimated to be a few billion US dollars per year.

Giant magnetoresistance discovered by A Fert and Peter Grünberg in 1988 has resulted in the commercial production of small magnetic read heads. Now information can be stored in high-density 200 GB hard disks. This is a billion dollars industry.

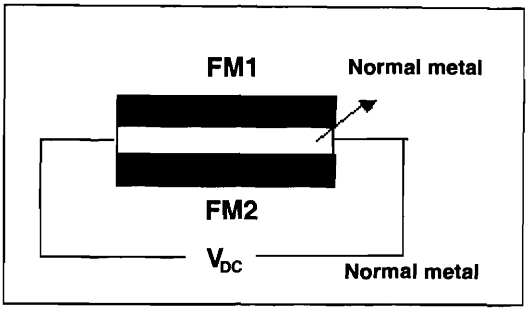
One can use GMR and Magnetic Tunnel Junctions (MTJs to be described later) for non-volatile memories in computers. At present there are three different types of memory elements, each having a specific characteristic. These are the semiconductor random access memory (SRAM) which provides high speed of access, the dynamic random access memory (DRAM) which provides high density and the Flash, which provides non-volatility or retention of memory even long after the power is switched off. Using magnetic tunnel junctions one can have a Magnetic Random Access Memory (MRAM) which will combine all the three characteristics. Rapid advances in materials and device technology are expected to make this a possibility. There will be a much bigger market running into hundreds of billion dollars for MRAMS.

Magnetic Tunnel junctions can be used to produce MRAMS which combine in them the advantages of high density of information storage, high speed of access and non-volatility

The small size and low power consumption of spintronic sensors allows the production of an on-chip array of sensors to detect low magnetic fields with high spatial resolution. Such devices can be used to detect very small changes in magnetic fields in magnetic biosensors, non-destructive testing, and position and document valida-

Magnetic sensors can be made for a variety of applications.

Figure 1. Spin valve.



tion including currency and credit cards, and in magnetic imaging.

Let us now consider the principles on which some of the spintronic devices operate.

Spin Valves

Consider a thin film FM1 of a hard ferromagnetic material separated from another thin film FM2 of a soft ferromagnetic material by a normal metal film (*Figure* 1).

A spin valve is a device which allows electrons of one spin polarization to flow through and obstructs the flow of electrons of the opposite spin polarization.

Let the direction of magnetization of the two FM regions be parallel. When a DC voltage is applied to the ends of this sandwich, a current travels parallel to the length of the sandwich. For the same applied voltage the current is large when the directions of magnetization of the ferromagnetic films are parallel. If the magnetization of FM2 is reversed by the application of a small magnetic field, the current drops in value. This happens because of interfacial scattering and channeling of the current. Such a device is called a spin valve as it allows electrons of one spin orientation to go through and prevents electrons of an opposite spin orientation to flow through. This indicates that the resistance $R\uparrow\uparrow$ when the magnetization in the two ferromagnetic films are parallel is smaller than the resistance $R\uparrow\downarrow$ when the magnetization of the ferro-magnetic films are antiparallel. The magneto-resistance percentage is defined as

$$MR\% = [(R\uparrow\downarrow\ R\uparrow\uparrow)/R\uparrow\downarrow] \times 100 \qquad (1)$$

The GMR in such multilayer films, discovered in 1988, forms the basis for the commercial applications described in the earlier section.

The same thin film technique can be used to make a F_1IF_2 tunnel junction with a hard ferromagnetic film as F_1, a soft ferromagnetic film as F_2 and a thin insulating oxide layer in between. These are called magnetic tunnel junctions (MTJ). One can achieve a very large change in tunneling conductance on the application of a magnetic field to reverse the magnetization in F_2. Such a junction has a higher sensitivity than the GMR resistive element. The tunnel junction consumes less power than the resistive GMR element. This is an advantage. But its high impedance makes it more susceptible to noise. These junctions can be used to form MRAMs mentioned in the earlier section.

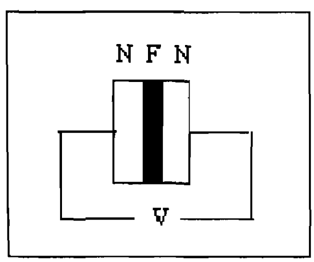
When unpolarized electrons pass through a spin filter, electrons with either up or down spins are filtered out.

Spin Filter

A schematic diagram of a spin filter is given in *Figure* 2. We have two bulk normal metal films separated by a film of Europium chalcogenide.

This is a N-F-N tunnel junction in which the application of a magnetic field to the Eu-chalcogenide film provides spin filtering. In the normal metal the electrons are unpolarized. The tunneling current through the Eu-chalcogenide film gets polarized because of the difference in the tunneling barrier heights between the normal metal and the Eu-chalcogenide for two spin orientations. 100% spin polarization was achieved at an applied field of 1.2 T with Eu–Se filter. There are other methods of realizing spin-filtering using spin-orbit coupling or hot electron transport across ferromagnetic regions. It has been proposed that spin filtering of Eu-chalcogenides with one electron quantum dots may form an important ingredient in quantum computing.

Figure 2. Spin filter. The ferromagnetic film is of Europium chalcogenide.



An MBD consists of a diode made of a p-type magnetic semiconductor and a n-type semiconductor. Its I-V characteristic depends on the polarization of the electrons.

Spin Diodes

These are two terminal devices in which the junction characteristics are altered either by polarization of the carriers or the polarization of the recombination centers. The recombination lifetime of the injected carriers will then depend upon the spin of the carrier. So the diode current in the forward direction is modified by the application of a magnetic field. While such an effect was seen even in p-n junctions of silicon the changes produced by the magnetic field in the forward current is only about 0.01%.

A magnetic bipolar diode is a p-n junction device in which one or both the regions are magnetic semiconductors. One such diode is p-Ga(Mn)As-nGaAs. The p-region is a magnetic semiconductor. A schematic diagram of operation of a magnetic bi-polar diode is shown in *Figure* 3.

The depletion region is shown between the two junctions. If the majority carriers on the n-side are not spin polarized then no current flows through the diode in the absence of the potential V If a non-equilibrium spin polarization is created in the n-region, either by shining circularly polarized light or by injection from the ferromagnetic metal, then one sees a larger current in the forward direction for the up-spin polarization than for the down spin polarization. This arises because the junction potential barrier is less for up-spin electrons than for down-spin electrons as shown in the *Figure* 3.

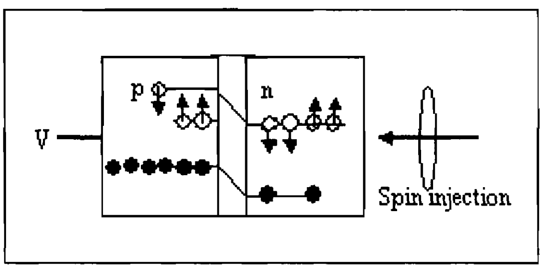


Figure 3. Magnetic bipolar diode: In the p-region on the left the conduction band is split due to the exchange interaction and the equilibrium population of the minority carriers (electrons represented by ○) depends on spin. The valence band is not split. Holes are shown as ● n region on the right is not exchange split.

Thus the forward current is modified depending on the sign of the non-equilibrium polarization in the n region. If the polarization is created by circularly polarized light then the open circuit voltage in the diode will depend on the direction of the circular polarization. This is called the spin-voltaic effect. Alternately the short circuit current will show giant magneto-resistance. However practical MBDs are still to be made and tested.

A magnetic bi-polar transistor consists of a non-magnetic semiconductor emitter and a collector separated by a base of a magnetic p-type semiconductor. The characteristics are different for up- and down- spin electrons.

Spin Transistors

We shall discuss two proposed schemes for spin transistors one in analogy with the bipolar transistor and the other in analogy with the field effect transistor.

In the bipolar transistor we have a semiconductor emitter, a magnetic semiconductor base and a semiconductor collector as shown in *Figure* 4.

Just as in a bi-polar transistor, we have an emitter, a base and a collector. The emitter and collector are non-magnetic n-type semiconductors. The base is a p-type magnetic semiconductor in which the conduction band is split due to exchange interaction. The junction between the emitter and the base is forward biased, while the junction between the base and the collector is reverse biased.

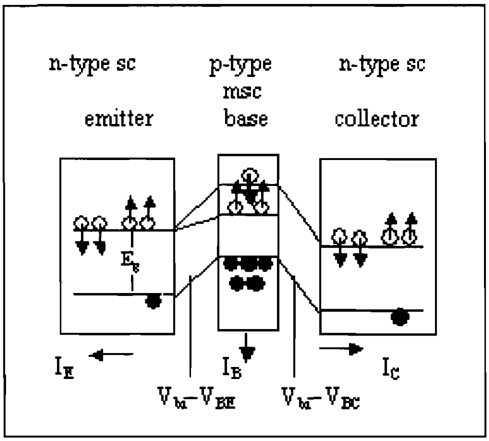


Figure 4. Schematic for a Magnetic Bipolar Transistor.

New materials with a wider range of spin polarization either in the metallic or semiconductor form will be desirable. These materials must have a Curie temperature above room temperature so that they will be ferromagnetic at room temperature. We also need materials with a large magnetization that can be reversed with the application of low magnetic fields.

If a non-equilibrium polarization is produced in the emitter, the spin-polarized electrons will flow towards the base. A few of these electrons recombine with holes in the base to produce a base current. The rest of the spin-polarized electrons will flow through the thin base to the collector. We may define a current amplification β as the ratio of the collector current IC to the base current IB. But this factor will have different values for positive and negative non-equilibrium polarizations. Such a transistor has not yet been realized.

The second transistor is the Datta–Das field effect spin transistor. A conceptual diagram of this transistor is shown in *Figure* 5. It consists of two ferromagnetic metals as source and drain.

The source and drain are ferromagnetic metals or semiconductors. The polarized electrons injected from the source travel along a quasi-one dimensional channel in a hetero-junction formed by two normal semiconductors. G is the gate electrode. In a semiconductor like InGaAs there is an absence of inversion symmetry in the crystal structure. In addition there is a lack of inversion symmetry in a heterojunction as the two materials on either side of the junction are different. Due to this lack of inversion symmetry the energy of an electron with a wave vector **k** in the xy plane and spin up is different

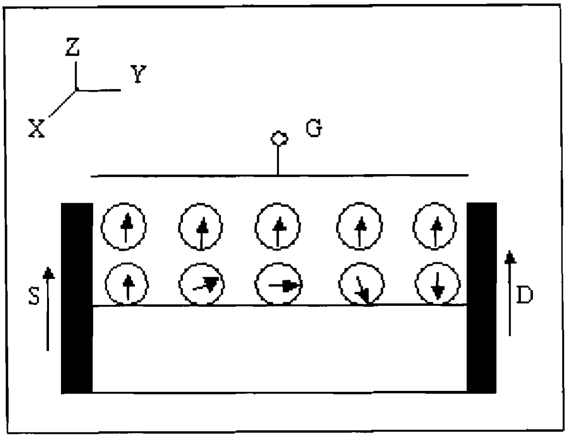


Figure 5. Schematic of Datta–Das Spin FET.

from the energy of the electron with wave vector **k** with spin down. This is equivalent to an effective magnetic field $\mathbf{B}(\mathbf{k})$. If the motion is made quasi-one dimensional parallel to the y axis, the effective magnetic field will be along the x direction and will cause the spin to precess in the yz plane as shown in the figure. If the spin precession frequency is very low, the electron will travel the length of the channel without an appreciable change in its spin orientation and will enter the drain as shown in the upper part of the figure. One can control the effective magnetic field by applying a voltage to the gate electrode. If the effective magnetic field is increased, the precession of the electron spin around the field is increased and the orientation of the spin may change by 180^o in travelling from the source to the drain as shown in the lower part of the figure. Then the electron will be reflected at the interface of the drain electrode and the channel, and the current flowing to the drain will be low. Thus we can control the current reaching the drain with a gate electrode. The Datta–Das spin FET is yet to be realized.

The Datta–Das spin FET is a transistor in which the gate voltage will control the precession frequency of the electron. Then the electron in travelling from the source to the drain may find its spin either parallel or anti-parallel to the spin of the electron in the drain. Accordingly, FET will have low or high resistance to the current flow.

There are other more complex proposals for spin FETs which will not be discussed here.

Materials for Spintronics

From the above discussion it is apparent that new materials with a wider range of spin polarization either in the metallic or semiconductor form will be desirable. These materials must have a Curie temperature above room temperature so that they will be ferromagnetic at room temperature. We also need materials with a large magnetization that can be reversed with the application of low magnetic fields.

Half-metallic materials are those in which the energy sub-band with one spin orientation is either empty or completely full (*Figure* 3 Part 1). Such materials have a

Half-metallic materials are those in which the energy sub-band with one spin orientation is either empty or completely full (Figure 3 Part 1). Such materials have a large magnitude of spin polarization.

large magnitude of spin polarization. Examples of such materials are CrO_2, Fe_3O_4. Colossal magneto-resistive materials such as Sr-doped $LaMnO_3$, and double perovskites have found wide application in GMR devices. An important class of materials currently under investigation are the Heusler alloys. They have a composition X_2YZ, where X and Y are transition elements and Z is a group III,IV or V element. Half-Heusler alloys have a composition XYZ.

Ferromagnetic semiconductors such as $CrBr_3$ are known to be highly spin polarized. Recent discovery of the ferromagnetic semiconductors, Mn-doped III-V compounds, has spurred a lot of interest. However, the solubility of the magnetic dopant in the III-V semiconductor is small. Excess dopant tends to form clusters. The clusters make it difficult to find the exact Curie temperature. Often the reported Curie temperatures of some materials can be ascribed to the formation of such clusters. Co-doped TiO_2 exhibits room temperature ferromagnetism and is optically transparent. The search for new magnetic semiconducting materials is being pursued vigorously.

Conclusion

The expectation that the manipulation of electron spin will lead to new classes of sensor, logic and storage devices has already been realized and such devices have been put to commercial use. The miniaturisation of conventional electronic devices is limited by the power dissipation. It has been suggested that spin current can flow in a semiconductor without energy dissipation. Hence one can dream of replacing existing electronic devices with spin-based devices with low power consumption. As we saw above, many new ideas for spin-based devices have been put forward. There have been rapid advances in understanding the underlying complex physics. However, it is not clear how many of the devices will be realized in a commercially viable form. One will have to wait for some more time to see if the promised potential of spintronics would be realized in practice.

Suggested Reading

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"Man is the animal that draws lines which he himself then stumbles over. In the whole pattern of civilization there have been two tendencies, one toward straight lines and rectangular patterns and one toward circular lines. There are reasons, mechanical and psychological, for both tendencies. Things made with straight lines fit well together and save space. And we can move easily – physically or mentally – around things made with round lines. But we are in a straitjacket, having to accept one or the other, when often some intermediate form would be better. To draw something freehand – such as the patchwork traffic circle they tried in Stockholm – will not do. It isn't fixed, isn't definite like a circle or square. You don't know what it is. It isn't esthetically satisfying. The super-ellipse solved the problem. It is neither round nor rectangular, but in between. Yet it is fixed, it is definite – it has a unity."

Piet Hein