Chapter 11
Spintronics

Abstract The field of spintronics is introduced and differentiated from magnetoelectronics. Augmentation of the capabilities of nanoelectronics by the addition of two spin degrees of freedom to the preexisting two charge degrees of freedom is explained. The spin degrees of freedom can also be used alone to create functional devices. The role of spintronics as a bridge between semiconductor ICs and magnetic storage is elucidated. The technologically recognized spintronic device working on giant magnetoresistance effect is compared with normal magnetoresistance. The operation of magnetic tunnel junction devices for providing high magnetoresistance ratios is described. Performance of MRAM is compared with SRAM, DRAM and flash memory devices. Besides fast access, the capability of spin transfer torque RAM to decrease the write current in comparison to MRAM is indicated. The main application areas of spintronics in computer hard disks and magnetic random access memory devices are highlighted.

11.1 Introduction

Information is stored in digital computers in two principal forms: in hard disks and as random access memory. Spintronic technology has contributed immensely to both types of memory by merging magnetism with electronics.

11.1.1 Defining Spintronics

Spintronics is the science and technology aimed at understanding and controlling a fundamental property of electrons known as the electron spin, in nanoscale structures and devices, and applying this knowledge to sensing, information processing, and communication circuits. Spintronics (abbreviated form of “spin transport electronics”), spin-based electronics, spin electronics, and flextronics are different names for the same specialization, viz., the utilization of intrinsic spin of the

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electron and related magnetic moment, along with its charge, in solid-state devices and circuits. Spintronics is sometimes called magnetoelectronics. However a deeper introspection reveals the difference between spintronics and magnetoelectronics because spins can be skillfully managed by electric as well as magnetic fields. So, magnetoelectronics is not spintronics in the strict sense of the term. Another similar term is “nanomagnetics”, which is primarily concerned with magnetic interaction between nanomagnets. Spintronics deals with the use of spin polarized currents in memory and logic devices [1]. Besides integrated circuits, the extensive spectrum of spintronics covers several disciplines such as mathematics, physics, material science, and nanomedicine.

11.1.2 Spintronics and Semiconductor Nanoelectronics

The spin is a quantum mechanical property of the electron. This quantum property has not received the deserved attention in mainstream nanoelectronics. In fact, electron spin is one of the three inherent properties of an electron. Its other two deep-seated properties are the mass and charge. The spin represents the rotation of the electron about its axis. It is the intrinsic angular momentum of the electron. It is parameterized by the spin quantum number m_s. Two values of spin quantum number are permissible: $m_s = \pm 1/2$. The electron is compared with a spinning top. Like a top, it can either spin clockwise or anticlockwise. The spin value $m_s = +1/2$ is called spin up. It is symbolized as an arrow pointing upwards. The spin $m_s = -1/2$ is known as spin down. An arrow pointing in the downward direction indicates this value

In spintronics, both the spin and charge degrees of freedom of an electron are used. The intent is to realize hitherto inaccessible functions to enable enhanced functionality devices. Adding the electron spin degree of freedom to electronics working with only charge degree of freedom augments the performance of devices. Thus semiconductor nanoelectronics is based only on electronic charge. Spintronics is a further step ahead because it uses electron spin apart from its charge to extend the capability. New functionalities are therefore expected from semiconductor devices that make use of both charge and spin.

As we know, electron spin can have one of the two orientations, up or down. Currents or voltages can have one of the two values, high or low. Thus the two states of spin, up or down, combined with the two states of the current/voltage, high or low, sums up to four possible states. Therefore, instead of the binary states in digital electronics, one has quarternary states in spintronics. These states can be expressed as: down-low, down-high, up-low, and up-high. They are called quantum bits or qbits. The doubling of the number of states provides higher operating speed, and greater processing power. It increases the memory density and thereby the storage capacity. However, it is necessary that electron spin can be controlled efficiently much like the electronic charge in electronics, for practical applications.

Today, information technology is based on the charge degree of freedom of electrons for processing information in semiconductors (a part of electronics) and their spin degree of freedom for mass storage of information in magnetic materials (a component of spintronics). Thus, spintronics bridges two main disciplines underpinning information technology. These two disciplines are: (i) semiconductor devices and integrated circuits and (ii) magnetic information storage. By doing so, it brings nonvolatility to semiconductor-based circuits, an essential requirement for reducing power in many applications. It also introduces the concept of circuit to magnetic storage field. Other potential applications of spintronics are in quantum computation and in the development of the quantum computer.

Spintronics is primarily based on magnetism and magnetic materials such as iron, cobalt, and nickel. Such materials are not normally used in semiconductor electronics. Hence, problems concerned with etching and patterning thin films of these materials and their unification into the silicon process are of paramount significance for manufacturing spintronic devices.

11.1.3 Branches of Spintronics

Metallic spintronics has pervaded all the present-day reader heads of hard disks in computers. Metal-based spintronic devices can function as switches or valves. But they cannot amplify signals like semiconductor electronic devices. Therefore, efforts are needed to fabricate semiconductor spintronic devices which could function at par with or better than their semiconductor electronic counterparts. Further, spintronic devices need to be seamlessly assimilated with traditional semiconductor electronic components.

Semiconductor spintronics is still in infancy. By producing ferromagnetism in semiconductors, one can build devices such as light-emitting and laser diodes for light-wave communication systems, transistors, logic and memory chips. Remote sensor systems can be constructed employing magnetic detection with on-chip circuits for signal processing and optical communication done off-chip [2]. Spintronics utilizing semiconductors offers opportunities for integrating the developed devices directly with semiconductor nanoelectronics. Furthermore, the magnetic properties are controllable by electric field instead of the magnetic field leading to smaller devices than metallic spintronics.

Semiconductor spintronics includes three types of semiconductor materials. First category is the nonmagnetic semiconductors. Second class is magnetic semiconductors. Third group is a hybrid combination consisting of metal with semiconductor. A magnetic semiconductor is a material in which both electron charges and electron spins can be controlled. It is made by doping a semiconductor material with magnetic impurities. Not all semiconductors can be rendered magnetic by the doping method. Moreover, some of these semiconductors have a very low Curie temperature above which magnetic properties are lost. A few semiconductors which show Curie temperature above room temperature are: GaP:Mn, ZnO:Co, TiO_2:Co, etc. [3].

11.2 Giant Magnetoresistance (GMR) in Magnetic Nanostructures

A spintronic device which is already established industrially is the GMR sandwich structure. It is widely used in magnetic sensors. It is called the spin valve or GMR valve. Data storage technology has vastly benefitted from it. Spintronic technology has already revolutionized memory storage of our computers in the form of hard disks utilizing the giant magnetoresistance effect

GMR effect is a quantum mechanical magnetoresistance effect. By magnetoresistance (MR) effect is meant the change in resistance of a conductor subjected to an applied magnetic field. In magnetic materials like iron, cobalt and nickel, an increase in resistance is observed to the flow of current parallel to the lines of magnetization, and a decrease in resistance in the perpendicular direction; hence called anisotropic magnetoresistance (AMR). Usually, the MR effect is very small ~2–5%.

GMR is observed in magnetic sandwiches/multilayers formed by stacking alternating layers of ferromagnetic and nonmagnetic metals (Fig. 11.1). An example is single crystal Fe/Cr/Fe sandwich having (100) orientation. Another example is (100) oriented Fe/Cr multilayer. The thickness of the individual layers is only a few nm. Hence, they comprise only a small number of atomic layers. It is not noticed in thicker layers outside nano domain. The change in magnetoresistance in GMR effect is much higher than in normal MR effect. It is around 10–80%. In most modern GMR devices, it is 20–25%. The magnetoresistance is found to decrease drastically in the presence of a magnetic field.

When the external magnetic field is not applied on the nanostructure, the direction of magnetization of the adjoining ferromagnetic layers is antiparallel. This

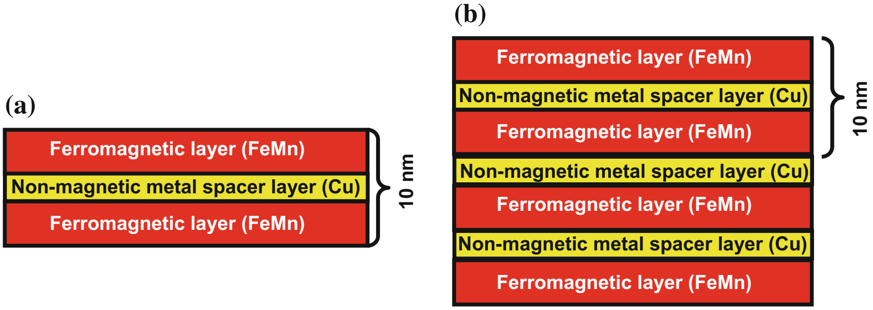

Fig. 11.1 Layered structures of GMR devices: **a** trilayer and **b** multilayer

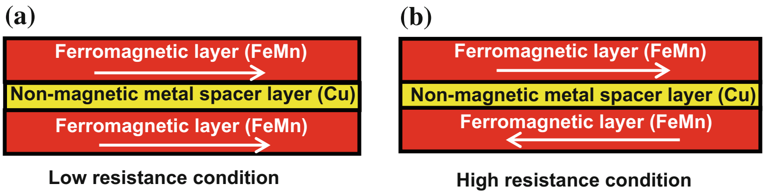

Fig. 11.2 Two possible magnetization states in a GMR structures: **a** parallel and **b** antiparallel

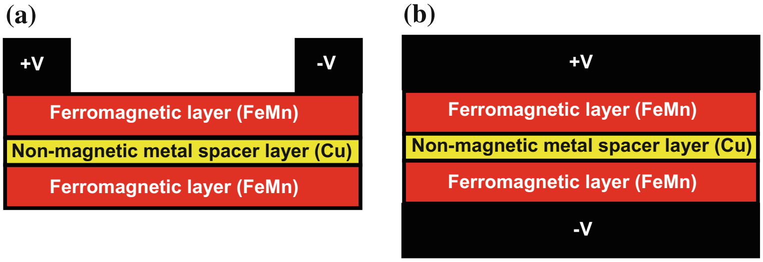

Fig. 11.3 Two current directions in a GMR structure: **a** current-in-plane (CIP) and **b** current-perpendicular-to-plane (CPP)

results in higher magnetic scattering and therefore higher electrical resistance. On placing the nanostructure in a magnetic field, the magnetization of the adjacent ferromagnetic layers becomes parallel amongst them. As a consequence, magnetic scattering is reduced and so also the electrical resistance.

Figure 11.2 shows the parallel and antiparallel magnetization states in GMR structures. Further, there are two possible current flow directions in these structures, in-plane and perpendicular to it, as shown in Fig. 11.3.

A spin valve is a multilayer GMR structure, which changes its resistance in accordance with the relative alignment of its constituent layers in the presence of an applied magnetic field. There are three kinds of spin valve structures (Fig. 11.4): top, bottom and symmetrical depending on which ferromagnetic layer in the structure is soft and can undergo orientation change in an external magnetic field. Figure 11.4a shows the top spin valve structure. In this structure, there are two ferromagnetic layers separated by a nonmagnetic spacer layer. The magnetic orientation of the upper ferromagnetic layer is fixed and unalterable. It is held in this condition by the nearby antiferromagnetic layer. Hence, the upper ferromagnetic layer is said to be magnetically hard. It is the pinned layer. However, the lower ferromagnetic layer is free to orient in the presence of a magnetic field. It s known as the free layer, and is magnetically soft. Due to the fact that the top ferromagnetic layer is magnetically hard, the structure is called top spin valve. In the bottom spin valve, Fig. 11.4b, the lower ferromagnetic layer is magnetically hard and the upper one is soft. In the symmetrical spin valve, Fig. 11.4c, both the upper and lower ferromagnetic layers are hard whereas the central ferromagnetic layer is soft.

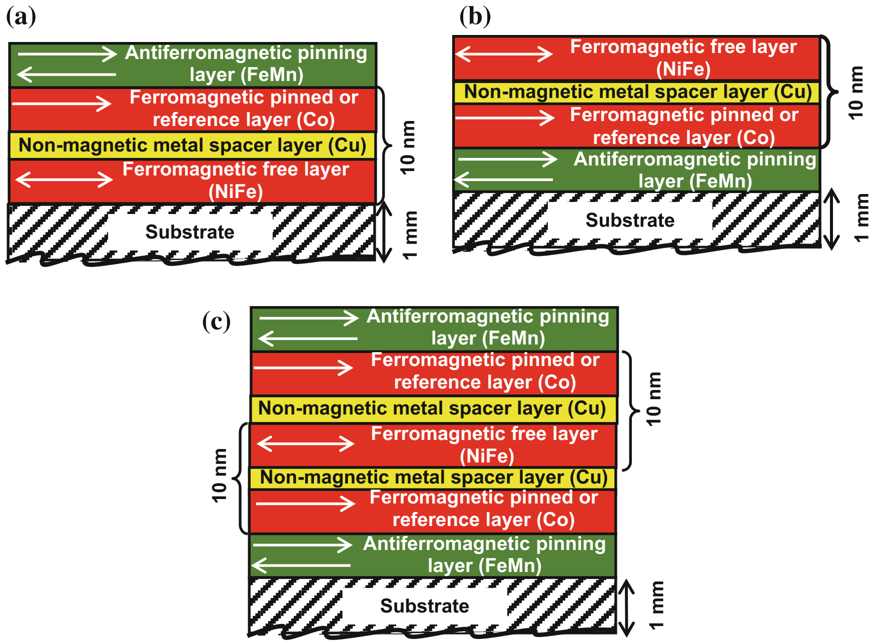

Fig. 11.4 Spin valve structures: **a** top, **b** bottom and **c** symmetrical

In the beginning stages, the films used for GMR studies were deposited by molecular beam epitaxy, which is a sophisticated and expensive technique. However, it was soon realized that GMR effect was also displayed by films obtained from simpler and inexpensive sputtering methods. Co/Cu layers were found to exhibit much pronounced GMR effect [4].

11.3 Magnetic Tunnel Junction (MTJ)

The MTJ is a thin film magnetoresistive device. It consists of two ferromagnetic electrodes made of, e.g., CoFeB, and separated by a thin insulating barrier layer (AlO_x or MgO) of thickness ~ 1 nm. Such a small thickness corresponds to barely 5–10 atomic monolayers [5], Fig. 11.5. The AlO_x layers are formed by depositing elemental aluminum and subjecting it to plasma oxidation. One of the two ferromagnetic electrodes has its magnetic orientation fixed by coupling with an antiferromagnetic pinning layer. This ferromagnetic electrode of fixed magnetic orientation is called the pinned or reference layer. The other ferromagnetic electrode can respond freely to external magnetic field. This electrode with reversible magnetization is therefore called the free or recording layer [6].

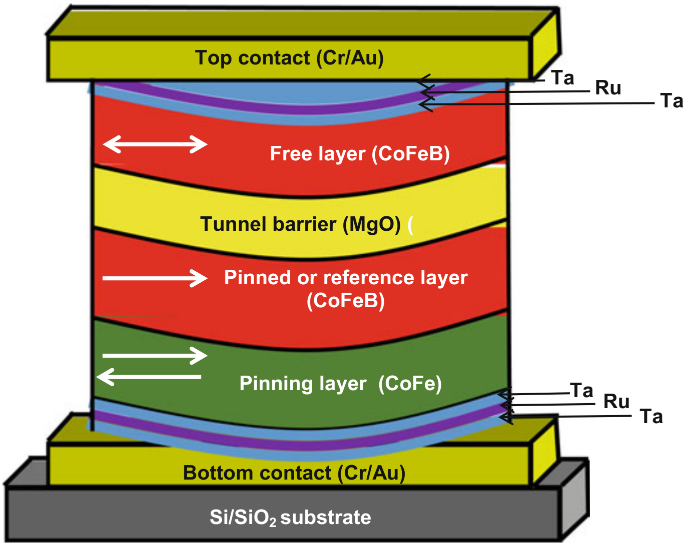

Fig. 11.5 Cross-sectional diagram of a magnetic tunnel junction showing the constituent layers

Under the influence of an applied magnetic field, the relative magnetic orientation between the two electrodes is altered. When the orientations of two electrodes are parallel, resistance of the structure is minimum and hence the tunneling current flowing through it is maximum. If they become antiparallel, the resistance increases, and therefore the current decreases. Magnetoresistance ratios are typically ~100–200% which is much higher than achieved in GMR. Magnetic tunnel junctions are used as read/write heads for disk drives.

MTJ sensors must be differentiated from the current perpendicular-to-plane GMR sensors. The main point of difference is that the GMR sensor works on the spin-dependent scattering effect. This effect occurs in the ferromagnetic layers as well as at the ferromagnetic/nonmagnetic interfacial regions. MTJ is based on the spin-dependent quantum mechanical tunneling. This tunneling takes place across a thin potential barrier.

11.4 Magnetic Random Access Memory (MRAM)

In Sect. 11.2, application of spintronic technology in computer hard disks was described. But digital data are stored in computers in different ways depending on the frequency of access, the speed of access, the period of storage necessary and volume of data to be accumulated. Data in hard disks need not be always accessed. Also, these data need not be instantly available to the computer. But they must be preserved for a long time. Further, it is essential that a high data density must be provided in the range of terabytes so that large quantities of data can be amassed. The need for long-term storage of data makes it mandatory that data is not lost when the power is switched off. Such type of memory is said to be nonvolatile. The hard disk memory is slow to access because the read/write magnetic head contains moving mechanical components. In a computer, these are the equivalents of the needle in an audio record player or the laser of a compact disc player. Access requires a time span of a few milliseconds. On the contrary, data that are required by the computer processor to execute its operations must be immediately available, i.e., fast access must be provided to these data on nanosecond time scale. But these data need not be everlastingly stored after the computer is switched off. So, a volatile memory can be used. These volatile memories are based on semiconductor devices. An externally applied electric field pushes electrons into or pulls them out of capacitors to create a charge pattern for encoding the data. This kind of memory is referred to as random access memory (RAM). A limitation of this memory is that it cannot be downscaled below a certain limit. The impediment to downscaling is that it is charge dependent. Below a limiting value, the signal-to-noise ratio increases to intolerable proportions. In opposition to data stored in charged/discharged states of capacitive devices, data stored in the form of relative orientation of magnetization of two magnetic layers is more appropriate for downscaling.

In a computer, SRAM (static RAM) is fast in operation but volatile. More memory density at cheaper cost is available from DRAM (dynamic RAM) but it is also volatile and needs periodical refreshing. However, one type of RAM, which is non-volatile is the flash memory. Flash memory is non-volatile but is still comparatively expensive. It is used in mobile phones. It suffers from slow speed and low persistence. A memory system, which combines the best features of the different types of aforementioned types of memory will be non-volatile like hard disks and will provide fast access like RAMs.

A major application area of spintronics is non-volatile memory devices such as magnetoresistive random access memory (MRAM), Fig. 11.6. Spintronic devices operate according to a simple scheme involving three stages: (i) writing the information as a particular orientation of spin, either up or down, (ii) transference of the written information by conduction of electrons along a circuit, and (iii) reading or recovery of the information. The spin orientation of electrons is preserved for a relatively long interval of time. It is not erased after the power source is removed. Therefore, it is useful for exploitation in memory storage. MRAM provides greater storage density, reduced power consumption and non-volatility. MRAM suffers from manufacturing reliability in the less-than-1 nm thick dielectric film separating the ferromagnetic electrodes of MTJ. So, the memory vanishes in less than a year.

In MRAM, the information is written by magnetic field produced by electric current. The information is stored in the direction of magnetization. The information is read through magnetoresistance changes caused by spin polarized currents.

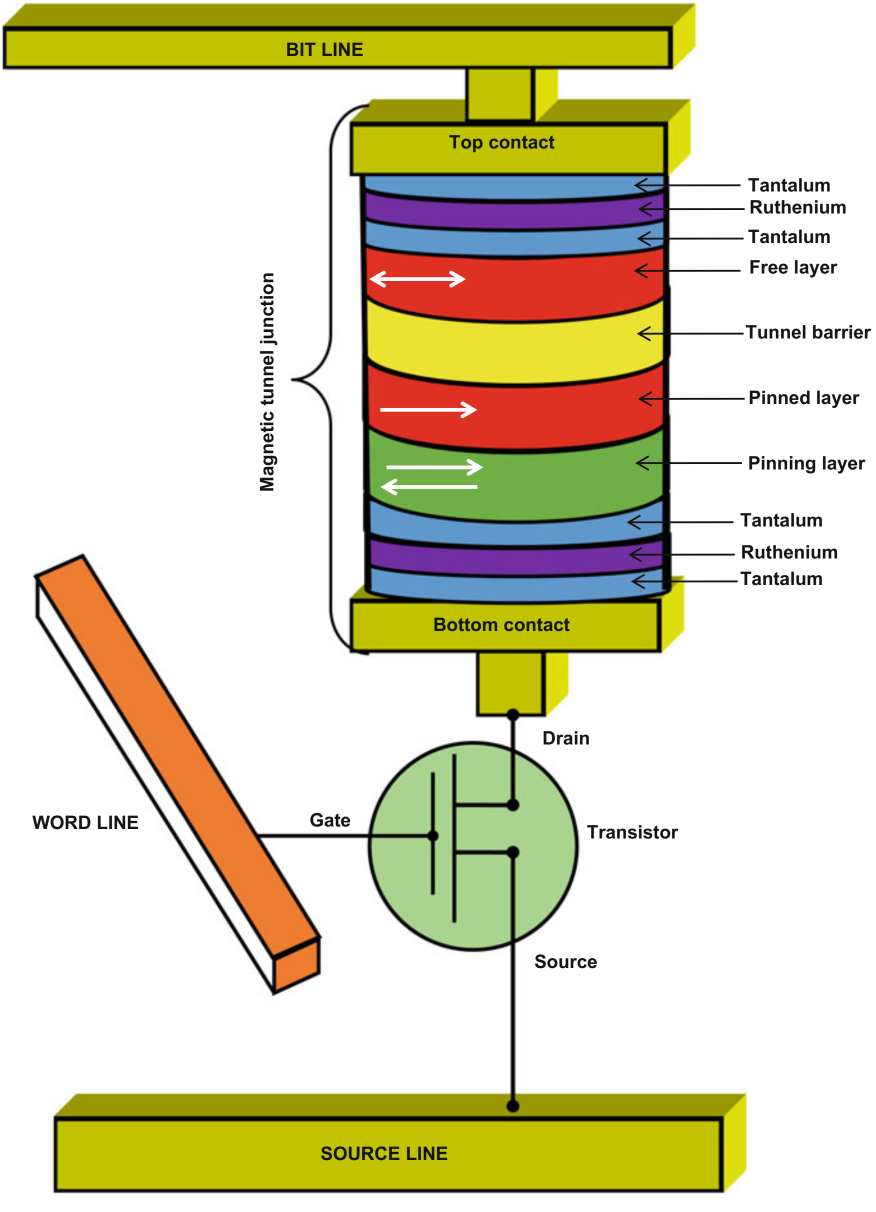

Fig. 11.6 MRAM cell using magnetic tunnel junction. Information is written by manipulating the magnetization of the elements through magnetic fields produced by the currents flowing in the bit and word lines. Information is read from voltage measurements across these lines. For bit selection, the word line and transistor are used

11.5 Spin Transfer Torque Random Access Memory (STT-RAM)

Generally an electric current is unpolarized consisting of half the total number of electrons in spin up position and the remaining half in spin down position. If by any means, the number of electrons in spin up or spin down position is increased to >1/2, the current is said to be spin polarized. In STT-RAM, a spin polarized current is used to change the magnetic orientation of the free layer in an MTJ. Instead of using a magnetic field as a read/write head, information is written electrically and also read electrically. By getting rid of the power-hungry read/write head and moving parts, the memory system becomes more rugged. Thus it provides fast-access, nonvolatile data storage. Power consumption may not appear to be a serious concern in a mains-operated desktop computer but is definitely not a trivial anxiety matter in a battery-operated laptop computer or mobile phone. Efforts have been constantly made to decrease the writing current of the MTJ storage element. At the same time, thermal stability for data retention and other functions must be retained. A writing current density of $1\text{–}2 \times 10^6$ A/cm^2 is reported for in-plane MTJ materials [1].

STT-RAM promises all the advantages of MRAM with scalability beyond 65 nm, thus providing a universal memory. This is possible by reducing write current and also through simpler memory architecture and manufacturing than MRAM. ST-RAM provides access times ~ 10 ns along with high endurance.

MRAMs of today vastly differ from the magnetic memories of bygone years. Earlier memories detected the storage state by an inductive signal. Today's MRAM does the same utilizing either the AMR effect, GMR effect or is based on magnetic tunnel junctions. These modifications help in two ways. First, the big coils are eliminated from the memory. Second, the readout sensitivity is greatly enhanced.

11.6 Discussion and Conclusions

Presently DRAM is used as the main memory, SRAM as cache memory along with hard disk or solid-state drive. The speed gap between these memories limits the performance of computers. Using MRAM, a new memory hierarchy can be designed. The speed gap can be reduced due to the high speed and large capacity obtained from MRAM [7].

Three pertinent research areas of spintronics are: (i) Improvement in performance of present-day GMR and magnetic tunnel junction devices by exploring new materials.(iii) Designing and fabricating improved high-density, highly reliable, long life, low cost, and low power consumption MRAMs. Radiation-hard MRAMs are required for space applications. (iii) Paying attention to semiconductor spintronics so that active device functionalities can be built in spintronics.

Review Exercises

11.1 What is the full form of ‘spintronics’? What are the other names by which ‘spintronics’ is called?

11.2 Define spintronics. What is the difference between spintronics and magnetoelectronics?

11.3 Name two intrinsic properties of electron besides its spin. What are the two allowed values of electron spin and how are they represented?

11.4 Explain how does spintronics extend the capability of semiconductor nanoelectronics by adding two spin degrees of freedom to the existing two charge degrees of freedom. What advantages accrue from the additional degrees of freedom?

11.5 How does spintronics act as a bridge between semiconductor integrated circuits and magnetic storage devices? Elaborate.

11.6 What are the problems faced in incorporating magnetic materials used in spintronics into semiconductor nanoelectronics?

11.7 What are the application areas of metallic spintronics and semiconductor spintronics? Which of the two branches of spintronics is still in infant stage?

11.8 Name a spintronic device, which is established industrially. Where is it used?

11.9 What is magnetoresistance effect? What is the meaning of ‘anisotropic magnetoresistance (AMR)’? What is the extent of change in resistance?

11.10 How does giant magnetoresistance effect differ from normal magnetoresistance effect? How much does the degree of resistance change produced in GMR differ from that in AMR? Is GMR restricted only to films of thickness in the nanoscale?

11.11 Explain the origin of GMR effect in terms of the parallel/antiparallel alignment of adjacent ferromagnetic layers.

11.12 Does GMR effect only take place in nanostructures fabricated by molecular beam epitaxy? Name a less expensive method of producing such nanostructures.

11.13 A magnetoresistive device can provide a much higher magnetoresistance ratio than the GMR device. What is this device called? What value of the ratio is achieved with this device?

11.14 Describe how are the different layers of a magnetic tunnel junction arranged. How is the magnetization of one layer fixed? How does the free layer respond to an applied magnetic field? What is the effect on magnetoresistance of this device in a magnetic field?

11.15 What is the main application of spintronics? What are the three stages in the operational scheme of spintronic devices?

11.16 How is information written in MRAM? How is it read from MRAM? How does MRAM compare in performance with respect to SRAM, DRAM and flash memory?

11.17 What is meant by spin polarized current? Where is it used? In what ways is STT-RAM superior to MRAM?

11.18 What kind of tasks the metallic spintronic devices cannot perform? Why is it necessary to develop semiconductor spintronic devices?

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