Chapter 10
Nanoelectronics

10.1 Introduction

In Chap. 9 (also see Fig. 9.1), we saw that the sizes of the electronic devices like transistors are shrinking accompanied by the increase of their density per unit area. With increased device density, in general, the cost of the product not only goes down but the device performance also improves. The performance is limited by the increased heat generation which in turn would restrict the size of the device that should be made. Further, as we go on reducing the size the physics of low dimensional materials does not remain the same as for the bulk according to the discussions in the previous chapters. In fact this gives rise to new nanodevices which would be discussed in this chapter just to understand the basic principle behind their peculiar behaviour which is not seen in the microdevices. Although very interesting, we shall not discuss the nanodevices in which carbon nanotubes or graphene are being used to obtain more efficient devices. Here we are restricting only to certain phenomena rather than special nanomaterials in the devices.

After the discovery of solid state transistor by Bardeen, Brattin and Schockley, revolutionary changes occurred in the field of electronics. Bulky, power hungry, expensive vacuum tubes based equipment slowly got replaced with tiny, less power consuming, light weight devices. This made it possible to produce portable, space saving, compact equipment. Today one can have personal wristwatches, calculators, portable computers (laptop), mobiles, stereos, videos etc. due to advances in electronics and related areas. Satellites, space missions and internets are unimaginable without solid state electronics. It was realized as early as 1958 that one could go on shrinking not only the sizes of individual device but fabricate large circuits on a single ‘chip’ as an ‘IC’ or integrated circuit (Chap. 9). Extrapolation of these ideas and development in device fabrication techniques like lithography, not only made it possible to fabricate Very Large Scale Integration (VLSI) of electronic devices and circuits but also faithfully produced large quantities of them commercially.

S.K. Kulkarni, *Nanotechnology: Principles and Practices*,
DOI 10.1007/978-3-319-09171-6_10

This makes it possible for the manufacturers to warrant their products for uniform performance.

In fact as early as in 1960, Moore predicted a trend in electronics device shrinkage which is popularly known as Moor's law which was discussed in Chap. 9. It can be noticed that after 2000 A.D. there has occurred a deviation from the Moor's law. This is quite easy to understand. One can go on reducing the size with the limit of an atom, but there is certainly a limit to the size below which properties of materials are not independent of size. We know it now that this is where the 'nanoscience' and 'nanotechnology' take over microelectronic.

Next revolution is expected in computers with what is known as nonvolatile memory by which we shall not loose any data being stored on a computer if there is a sudden electricity failure or we forget to save the entries. We may also have what is being researched presently as quantum computers which will be much more powerful than the existing computers. Such computers will use the fruits of nanotechnology.

The flat panel television or computer monitors are products of nanotechnology. Even the coatings used on screens of TV or monitors can be of nanoparticles, which have better properties in terms of colour quality and resolution than micro particle coatings.

Here we shall discuss a few peculiar phenomena/nanodevices achieved due to reduced dimensionality (confinement effects) as well as realization through the developments in the lithography techniques to fabricate nanodevices and chips.

10.2 Coulomb Blockade

Materials are often classified as metals, semiconductors and insulators, according to their ability to let current flow through them. Conductivity is defined in terms of the properties of electrons (their number, effective mass, scattering etc.) in the solids and is given by

$$\sigma = \frac{Ne^2\tau}{m^*} \tag{10.1}$$

where σ is electrical conductivity, N – number of electrons per cm^3, e – electron charge, τ – relaxation time and m^* is effective mass of electron.

Resistivity is the inverse of conductivity. Metals are characterized by very low resistivity ($\sim 10^{-6}$ Ω.cm). Semiconductors have medium resistivity (few Ω.cm) and insulators have large resistance ($>10^3$ Ω.cm). The resistivity (or conductivity) in solids can be measured in principle by connecting electrically conducting wires to solid material of known geometry, applying a voltage difference across it and measuring the current flowing through it (Fig. 10.1) (Box 10.1).

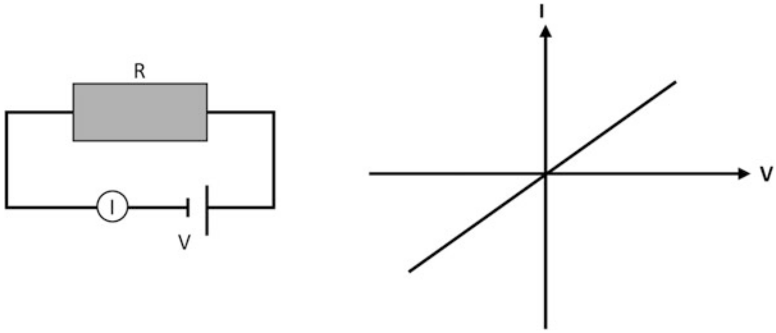


Fig. 10.1 Resistance measurement of a typical metal resistor

Box 10.1: Can Nanoparticles Be Considered as Metals?

Measurement of current through materials having dimensions in nanometer range is a difficult task. Particularly, measurements on single nanoparticles are difficult. Apart from the experimental difficulties one needs to also understand the meaning of metallic nature of particles at reduced dimensions. It is important to know, as the particle size reduces, does the material become semiconductor or insulator and at what size it deviates from being a metal. Is there any other characteristic of materials which can allow us to know when the metal stops being a metal as the particle size reduces. Indeed if one can try to carefully look at the elements in the periodic table, it can be seen that all the atoms have characteristic ionization potential or energy. The elements which form metals are characterized by the low ionization energy. The elements which form semiconductors have ionization energy larger than metals but smaller than that for the insulators. This is depicted in Fig. 10.2. Ionization energy is defined as the energy required to remove an electron from the atom/molecule/cluster/solid to vacuum level.

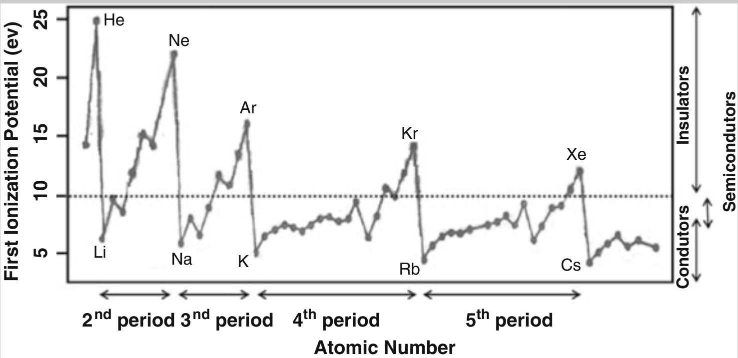


Fig. 10.2 Elements in the periodic table plotted according to their increasing atomic number and their first ionization potential

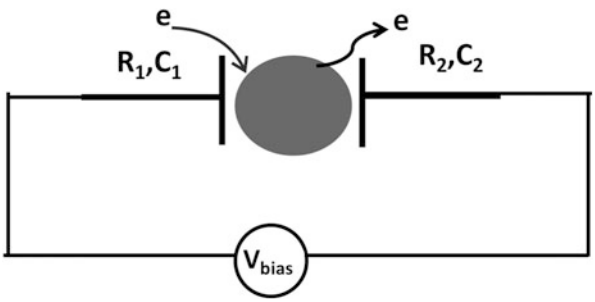


Fig. 10.3 Metal cluster or semiconductor quantum dot placed between the electrodes in order to measure the electron current flowing through the circuit

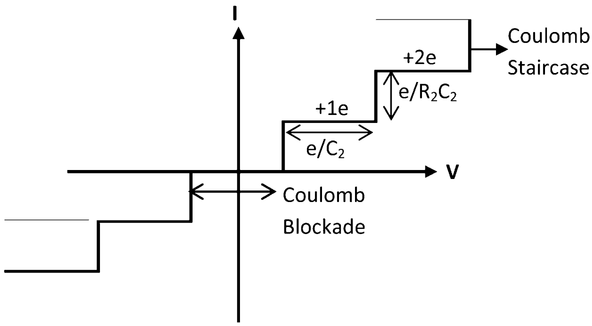


Fig. 10.4 Coulomb blockade and staircase for a quantum dot

If we reduce now the dimensions of metal piece (or introduce a semiconductor nanoparticles or quantum dot) to ~100 nm or less and wish to measure its conductivity, then it is useful to put metal electrodes (capacitors) on either side so that direct contact between electrodes and metal particle is avoided (Fig. 10.3). This enables to deduce the correct details of electronic structure. There appears then a region around zero voltage for which there is no current flow (Fig. 10.4). This phenomenon is known as *Coulomb blockade*. This can be understood as follows.

With the arrangement as in Fig. 10.3, there will be step-like current flow as shown in Fig. 10.4.

The electrostatic energy *E* (charging energy) of a parallel plate capacitor having capacitance '*C*' is given by

$$E = \frac{e^2}{2C} \tag{10.2}$$

For small value of the capacitance and low thermal motion of electrons ($kT \ll e^2/2C$) the charging energy *E* will be significant. The small metal island connected to electron source and drain by tunnel barriers can be charged in such a way that only a single electron is transferred to it when voltage $\pm e/2C$ is applied. Below this voltage electron cannot be transferred (Fig. 10.5). Therefore the region of *no current* of low bias voltage is known as *Coulomb Blockade region*. Repeated tunnelling of single electrons produces what is known as *Coulomb Staircase*.

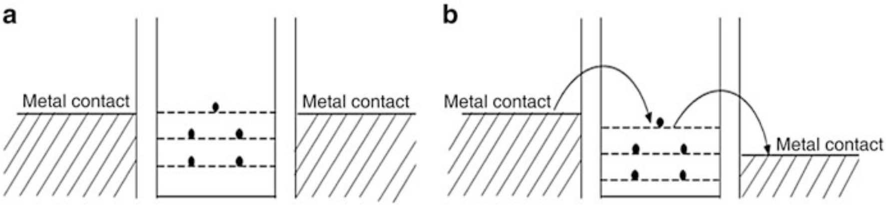


Fig. 10.5 (**a**) Current cannot flow; (**b**) Current flows due to the convenient alignment of the Fermi level positions in the contacts and the metal cluster or quantum dot

There are many examples now in which phenomenon of Coulomb Staircase has been demonstrated using quantum dots or metal islands.

The Coulomb blockade can also be very well understood from Fig. 10.5. When the Fermi levels on both the sides are at the same level, no current flows but the moment one of the electrodes as shown in the figure receives higher potential with respect to the quantum dot, the current can flow between the metal electrodes and the quantum dot. Similarly if the cluster is at higher potential compared to the electrode then the electrons from the cluster tunnel towards the electrode.

The single electron transistor is based on the phenomenon of Coulomb blockade.

10.3 Single Electron Transistor (SET)

Just as in a usual or classical micro size transistor (see Box 10.2) there are three main components of a single electron transistor viz. source, drain and gate. As illustrated in Fig. 10.6, the quantum dot is placed between the source and the drain. The gate controls the raising or lowering of the electron levels in the quantum dot through the gate capacitor by adding or lowering the number of electrons in the quantum dot. As the phenomenon of tunnelling and, hence, Coulomb blockade are the main phenomenon involved, the electrons are controlled precisely one by one and the name to the transistor is given as *Single Electron Transistor*. Different SETs are fabricated based on mainly the 'quantum dot' being used. The requirement is that there has to be nanostructure with discrete energy levels as in 'particle in a box' which takes place of the quantum dot so that a single electron control is achieved.

Box 10.2: Diodes and Transistors

We had seen earlier briefly that semiconductor materials can be doped with various elements which change their optical and electrical properties by introducing some electronic states in the energy gap between the valence and the conduction band. Even though in nanostructure of semiconductors the

(continued)

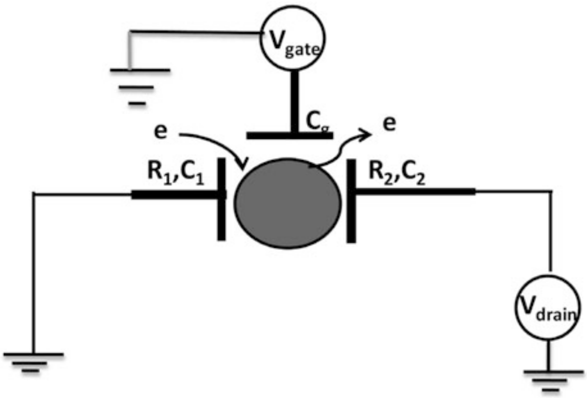
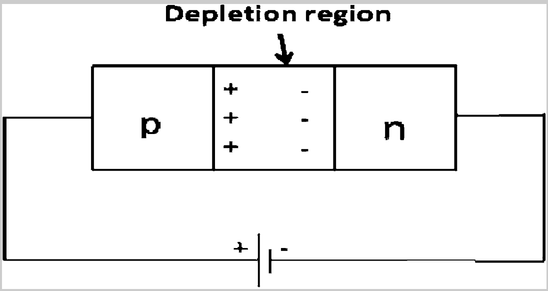


Fig. 10.6 Schematic diagram of a single electron transistor with three terminals

Box 10.2 (continued)
band gaps or overall electronic structure may change with dimensionality and shape, the dopants are still powerful means of altering their properties. The dopants may introduce extra electrons making the semiconductor 'n' type or introduce excess holes making it a 'p' type semiconductor.

The simplest and the earliest semiconductor device is a two-terminal diode in which, in a semiconductor material, under controlled diffusion of dopants a p-n junction is formed. Thus in the diode one side is 'p' type and other is 'n' type. This makes diode an asymmetric device. At the junction a depletion region is formed, as illustrated in Fig. 10.7.

Fig. 10.7 A p-n diode



This helps to make the diode forward biased (p connected to the positive terminal and n connected to the negative terminal) or reverse biased. By biasing through an external power source (battery), we are able to control the Fermi level and thereby the nonlinear electron or charge flow in the

(continued)

Box 10.2 (continued)
circuit. Diode is an asymmetric device and is able to allow the current in one direction but to block the current in the reverse direction. This can be seen from Fig. 10.8. Note that there can occur a breakdown known as Zener breakdown on the application of the large negative voltage.

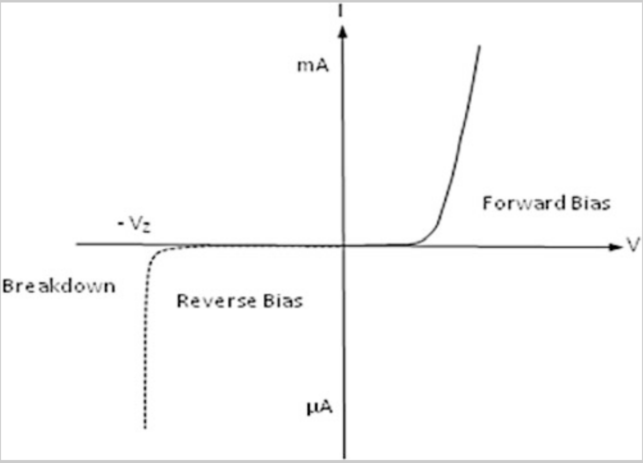


Fig. 10.8 Current flow with applied voltage in a p-n diode

Without going into further details about the diodes it can be just mentioned that the diodes are classified as Schockly diode, Schottky diode, Zener diode, photo diode, light emitting diode, Gunn diode, laser diode etc.

The next and most widely used semiconductor device is the three-terminal semiconductor transistor. It can be used to not only amplify the signal but also as a switching device. Historically, Julius Edgar Lilerfeld had patented in 1925 a field effect transistor (FET) in Canada and in 1926 and 1928 in USA. This was followed by another patent in 1934 by Oskar Heil in Germany. However John Bardeen, William Schockly and Walter Brattain at Bell labs made gold point contacts and observed in 1947 that they were able to get the large output signal compared to the input signal. They were given the Nobel prize in 1956. The device was referred to as a transistor by John R. Pierce because it can be looked upon as 'transfer resistor'. The increase of signal is nothing but 'gain'.

There are mainly two types of transistors viz. bipolar transistors and field effect transistors. The terminals of a bipolar transistor are called emitter, collector and base. In Fig. 10.9 an n-p-n bipolar transistor is schematically illustrated.

(continued)

Box 10.2 (continued)

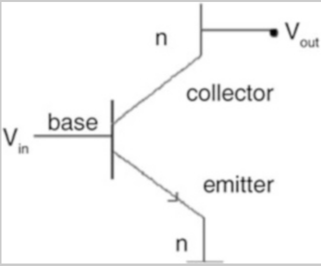


Fig. 10.9 Schematic illustration of a three-terminal bipolar semiconductor transistor

The field effect transistor (Fig. 10.10) has source gate and drain on the terminals. Current between source and drain is controlled by primarily the voltage at the gate.

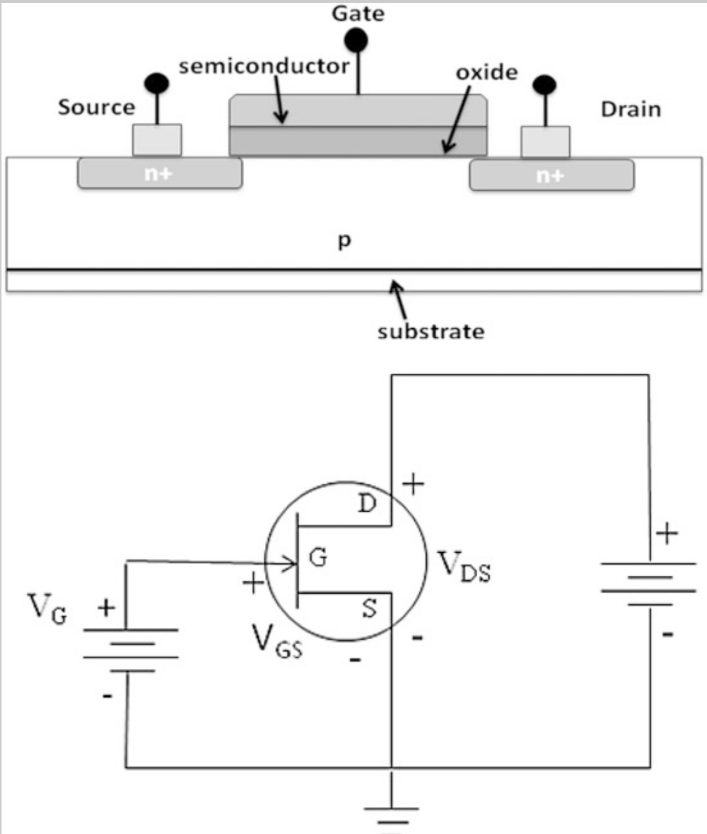


Fig. 10.10 Schematic illustration of a Field Effect Transistor

(continued)

Box 10.2 (continued)

The low operating voltage, hence power saving, has made transistors popular. Transistors also have high efficiency; they are reliable for repetitive operations and extremely long life. They are not affected by mechanical vibrations and render themselves in many applications. There is a huge variety of transistors such as Schottky transistor, bipolar junction transistor (BJT), insulated gate bipolar transistor (IGBT), avalanche transistor, Metal Oxide Field Effect Transistor (MOSFET) and so on. In recent years Carbon Nanotubes also have been used in Field Effect Transistor (CNFET). Transistors using organic semiconductors (OFET) also have been fabricated.

The transistors are lithographically patterned along with other components such as diodes, capacitors and interconnects to obtain densely packed integrated circuits (ICs).

10.4 Spintronics

The electronic devices with typical dimensions of few nanometers in either of three directions display not just the miniaturization but unique properties not known over last 5–6 decades since the beginning of solid state devices. Single Electron Transistor (SET), spin valves, and Magnetic Tunnel Junctions (MTJ) are conceptually new devices based on nanotechnology. Such devices are fast, compact, relatively cheap and finding their way to market. Spin valve type devices are already being used in personal computers to 'read' disk which have enabled to increase data storage capacity of hard disks. Interestingly, spin valve and MTJ are based on a concept which itself is growing into an area in itself known as spintronics or spin-based electronics or magnetoelectronics. Some potential spintronics materials are given in Box 10.3. It is well understood that an electron (or hole) has both charge and spin. However electronics has so far used only the charge property of electron (or hole) and spin has been neglected. It has been now realized in recent years that if spin of an electron (or hole) is taken into account, properly fabricated devices would lead to some superior devices. Using an external magnetic field, spin transport can be controlled. Advantage with spin is that it cannot be easily destroyed by scattering from collisions with other charges, impurities or defects. Many spin-based devices like Spin-FET, Spin-LED, Spin-RTD, optical switches with THz frequency, modulators, encoders, decoders, and q-bits for quantum computers are on the hot list of scientists and the technologists. We consider here devices based on Giant Magneto Resistance (GMR), spin valve, Magnetic Tunnel Junction (MTJ) and Spin Field Effect Transistor (SFET).

Box 10.3: Spintronics Materials
Some of the materials which have a potential in spintronics are summarized below.

1. II-VI semiconductors doped with transition metal ions (also known as Diluted Metal Semiconductors or DMS for short)
2. III-V semiconductors doped with transition metal ions (DMS)
3. Metal oxides with large band gap and doped with transition metals. For example TiO_2, SnO_2 doped with cobalt
4. Eu chalcogenides
5. Heusler alloys like NiMnSb, Mn_2CoGe
6. Ferromagnetic metal oxides like CrO_2, Fe_3O_4
7. $Mn_{11}Ge_8$
8. Lanthanum doped CaB_6

10.4.1 Giant Magneto Resistance

Giant Magneto Resistance (GMR) can be realized in the multilayers. Deposition of one kind of material over the other (sputtering, e-beam evaporation or electrochemical deposition are commonly employed techniques) of a few nanometer thickness, and repeating it several times gives rise to a multilayer. Multilayers are artificially created man-made materials. As can be seen from Fig. 10.11, such multilayers are characterized by the presence of a large number of interfaces. The properties of

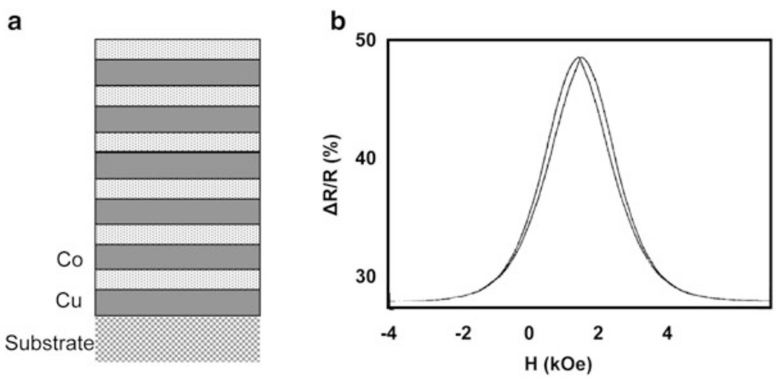


Fig. 10.11 (**a**) Schematic of a Co/Cu multilayer structure, (**b**) Magnetoresistance of the Co/Cu multilayer at room temperature

multilayers are, therefore, governed not only by the parent materials but also by their surface and interface properties.

Multilayers can be of metals, semiconductors, insulators, organic materials or combinations of these. Here we are interested in magnetic multilayers, though other types of multilayers also are interesting and have large applications.

Magnetic multilayers in which ferromagnetic layers of materials few nanometers thick are separated by comparable thickness metallic layers attracted the attention around 1988 when French scientist Albert Fert and German scientist Peter Grünberg observed that such ferromagnetic layers can be ferromagnetically or antiferromagnetically coupled. This gives rise to a magnetoresistivity which depends upon the orientation of the magnetic layers. Magnetoresistance (MR) is the relative change in electrical resistance of a material on the application of magnetic field.

It is usually defined as:

$$MR\,(\%) = \frac{R(0) - R(H)}{R(H)} \times 100 \tag{10.3}$$

where $R(0)$ is the resistance of the material when no external magnetic field is applied and $R(H)$ is the resistance of the material when external field of H is applied.

The change in the resistivity can be quite large and is known as Giant Magneto Resistance (GMR). Except few cases of anisotropic magnetoresistance, magnetoresistance in materials is usually quite low (less than even 0.5 %). However GMR can be as high as even 50–60 %. This is very effective in observing small changes in the magnetic field and useful as a read device of the magnetically stored data.

Obviously, the effect has found huge application in today's computers and can be considered as first direct application of nanotechnology. No wonder that both Fert and Grünberg received in 2007 the Nobel prize in physics for discovery of GMR.

In Fig. 10.11, Co/Cu multilayers are shown in which cobalt ferromagnetic multilayers are separated by copper layers. The corresponding magnetoresistance behaviour is shown in Fig. 10.11b. It can be seen that with the application of the magnetic field the resistance of the sample changes dramatically. This behaviour can be understood as follows.

Figure 10.12 schematically shows the mechanism due to which giant magnetoresistance occurs in magnetic multilayers. When magnetic layers are polarized in a particular direction, the carrier electrons with parallel spin pass through the material easily and resistance in such a case would be low for the flow of electrons. Thus alternate magnetic layers by the application of magnetic field would exhibit low resistance.

On the other hand if the alignment of magnetic layers is antiparallel to each other like in antiferromagnetic material, electrons, with spin parallel or antiparallel, are bound to see the layers of opposite spin and perceive the resistance to flow. Thus initially antiferromagnetically coupled magnetic layers would offer larger resistance as in (b) as compared to those that are ferromagnetically aligned as in (a). Depending

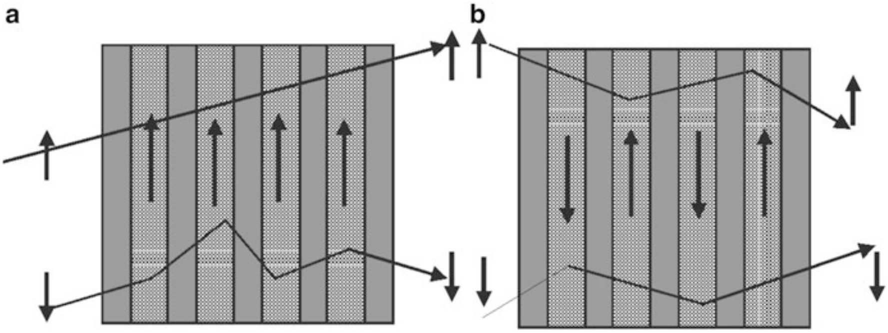


Fig. 10.12 Schematic of occurrence of magnetoresistance in magnetic multilayers with (**a**) ferromagnetic and (**b**) antiferromagnetic coupling. In Fig. (**b**) both up and down spins get scattered unlike in (**a**) where spin up suffer less scattering and the overall resistance in this case is less

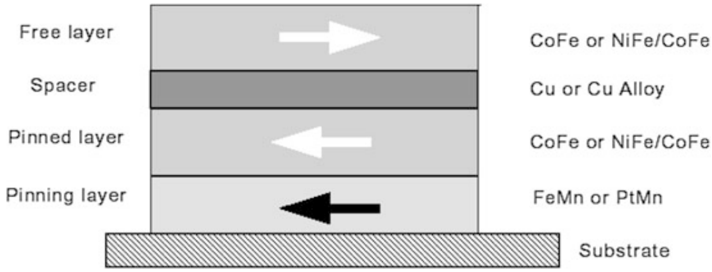


Fig. 10.13 Schematic of a spin-valve structure

upon the thickness of the interlayer (copper layers in this example), the magnetic layers can be coupled ferromagnetically or antiferromagnetically. There are many combinations of magnetic multilayers known now and have been used in computers.

10.4.2 Spin Valve

Based on the GMR effect, multilayer structures have been designed for various applications. Spin valve (Fig. 10.13) is a thin film made up of essentially tri-layers. One layer is a magnetically very soft material, meaning it is very sensitive to small magnetic fields. The other is made of a magnetically 'hard' meaning insensitive to fields of moderate strength. The central part of the sample consists of two magnetic layers (for example CoFe or NiFe), separated by a Cu spacer layer. One magnetic layer is pinned or exchange biased by an antiferromagnetic material (for example FeMn or PtMn). As the soft 'free' layer moves about due to applied field, the resistance of the whole structure can vary. Spin valves are commercially used in computer read heads. Their use has enabled to increase the data storage capacity of magnetic memory devices due to their ability to detect small magnetic fields.

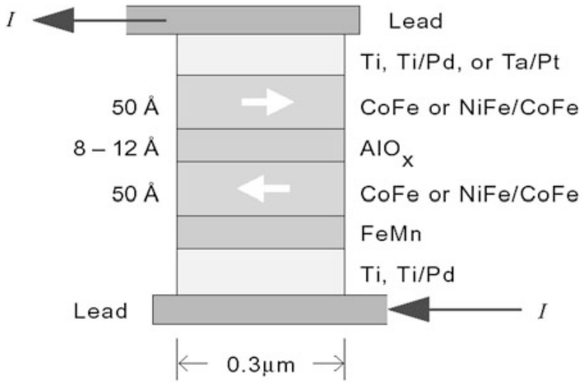


Fig. 10.14 Schematic of a magnetic tunnel junction

10.4.3 Magnetic Tunnel Junction (MTJ)

In the early 1990s, high magnetoresistance (MR) was discovered for magnetic tunnel junction (MTJ) material. MTJ material is made of at least two magnetic layers (Fig. 10.14) separated by an insulating tunnel barrier. The current flows perpendicular to the film plane. The best results have been achieved with aluminum-oxide tunnel barriers. Since the initial experimental discovery of MTJ material with promising MR, the technique of producing these materials, as well as key properties, has been dramatically improved. Tunnelling MR values are in the 20–50 % range.

Instead of using inorganic insulating barrier layers like aluminium oxide, attempts are also made to insert organic insulating layers to make MTJ devices. This can also lead to the fabrication of flexible organic devices in future.

10.4.4 Spin Field Effect Transistor (SFET)

The Spin polarized Field Effect Transistor (SFET) was first proposed by S. Datta and B. Das way back in 1990. In this case the source and the collector (or drain) are ferromagnetic or half metal materials. The electrons from the source are injected in a planer nonmagnetic metal and are to be transmitted through a planer non-magnetic metal to the collector. In the metallic layer the spin polarization gets reduced which can be controlled by the gate voltage. When the electron spins in the non-magnetic 2-D, metal are parallel to both source and collector. They are able to pass into the collector (on-state) and if they are antiparallel (off-state) then they are not able to pass into the collector or carry current. In fact the electrons in the non-magnetic 2-D metal layer precess (through an effect known as Rashba effect) and need to be controlled through the gate voltage. Realization of SFET took about two decades after it was proposed. Polarized beam of light was used to obtain spin polarized electrons from the source. It is expected that this will help in faster and efficient data processing.

10.5 Nanophotonics

When nanostructures (quantum dots, nanowires or 2-D thin films) or nanocomposites are used to produce light or detect light we are already dealing with a branch in nanoscience known as Nanophotonics. It is expected that one day we will have nanophotonic chips just like semiconductor chips in which light production, propagation, manipulation like amplification, filter, detection etc. can be performed on a 'nanochip'. Manipulation of signals would then be faster. The present research is towards achieving these goals. The interaction of light with wavelength smaller or comparable to the metal or semiconductor nanostructure sizes was discussed in Chap. 8. We already saw that some of the effects like localized surface plasmon resonance, surface polariton and exciton excitation occurred as a result of interaction of light with nanostructures. We also saw that, as a result of light confinement, there occurred Near Field Effect and consequently one could use it for overcoming the diffraction limit of microscopes. One also has possibility of using photonic crystals to manipulate light. The photonic crystals are abundant in nature through the peacock feathers, butterfly wings etc. The beautiful colours we see in these living animals are the result of periodic arrangement of some proteins which allows certain wavelengths of lights to pass through them and certain wavelengths are forbidden. This is similar to electron states in a semiconductor. We know that in a semiconductor, between the valence and the conduction band, there is an energy gap in which no electron states exist and is known as forbidden gap. It means that the electrons with energy between valence and conduction band are not allowed to propagate in the crystal. Similarly in a photonic band gap material, the photons of certain wavelength (or frequency) are forbidden to propagate. Thus a photonic band gap results. Such a gap can be created artificially by arranging nanoparticles of small uniform size in periodic lattice. The variation of size or dielectric constant is sensitive to optical gap and can be used to sense small variations in the photonic crystals.

Nanophotonics is currently a developing branch and there is plenty of scope to obtain novel materials and their structures to manipulate and propagate light through small structures for ultrafast communication systems.

Further Reading

G.W. Hanson, *Fundamentals of Nanoelectronics* (Pearson Education, Upper Saddle River, 2009)
O. Manasreh, *Introduction to Nanomaterials and Devices* (Wiley, Hoboken, 2012)
S.M. Sze, *Physics of Semiconductor Devices*, 2nd edn. (Wiley, New York, 1999)