Classification of solids on the basis of band theory

From the modification of the free electron model and taking into account the periodicity of lattice, i.e., from the kronig penny model, we concluded that atomic electrons in a solid are distributed into a number of energy bands separated from each other by forbidden gaps.

The width of energy bands is of the order of few eV. hence for a solid containing 10^23 atoms, the distance between the adjacent levels is nearly 10^-23 eV

According to pauli's exclusion principle, each energy level can be occupied by two electrons having opposite spins. Hence, usually the lower energy bands will be filled with electrons.

Depending on the nature of the band occupied and the width of the forbidden gaps , all solids are classified into conductors, semiconductors and insulators.

UNIT -5

SemiConductors

Classification of solids
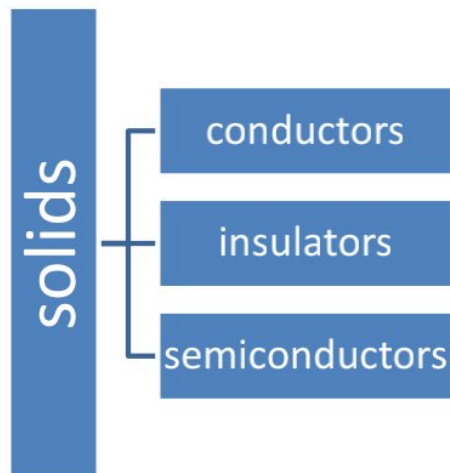
<mark>Conductors:</mark>

In some solids there are partially filled band above the completely filled lower bands. Such a band is formed from partially filled atomic levels as in the case of alkali metals like sodium.

A partially filled band may also result due to overlapping of completely filled and empty bands in the case of alkaline earth metals.

A large number of electrons of this band behave as free electrons and are conductors of electricity at all temperatures. Such solids are classified as conductors

Partially filled valance energy band is a feature of metallic conductors

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Insulators:

In some solids a number of allowed energy bands are completely filled and above these bands there is a series of complete empty bands, but between the highest filled and next empty band there is a forbidden energy gap.

If the gap is wide enough greater than 3eV then it is virtually impossible at all practical temperatures to thermally excite an appreciable number of electrons across this gap from the top of highest filled band to the bottom of lowest empty band.

All the bands are either completely filled or empty at any temperature and therefore an external electric field cannot cause any current. All solids having this character of binding are classified as insulators eg., NaCl and diamond with forbidden energy gap of 6eV

Semiconductors:

Semiconductors are materials whose electronic properties lie between metals and insulators

The electrical resistivity of these materials generally lies in the range of 10^{-2} to 10^{-9} ohm-cm at room temperature, which is between that of good conductors 10^{-6} and insulators 10^{14} ohm-cm

The electrical conductivity of a pure semiconductor is due to both holes and electrons.

Examples germanium silicon selenium, graphite etc.,

Intrinsic and extrinsic semiconductors, Dependence of Fermi level on carrierconcentration and temperature (equilibrium carrier statistics), Carrier generation and recombination, Carrier transport: diffusion and drift, p-n junction, Metalsemiconductor junction (Ohmic and Schottky), Thermistor, Hall effect, LED, Solar cell.

Based on electrical conductivity, materials are divided into conductors, insulators and semiconductors. Usually, metals are good conductors of electricity and all dielectrics are insulators. The electrical conductivity of semiconductors lie in between metals and dielectrics. Good examples for semiconductor are germanium and silicon. These elements belong to IV group in the periodic table. At 0 K, these elements are insulators, whereas at room temperatures they possess certain amount of conductivity. Pure germanium and silicon are called intrinsic semiconductors. By adding a small quantity of either III group or V group element atoms as impurity into pure Ge or Si, the electrical conductivity of the material increases. This impure semiconductor is called an extrinsic semiconductor.

INTRINSIC SEMICONDUCTORS- CARRIER CONCENTRATION

Pure germanium or silicon crystal is called an intrinsic semiconductor. Each semiconductor atom possesses four valence electrons in the outermost orbit. To get stability, each of these atoms has to get eight electrons in the outermost orbit, so that each atom makes four covalent bonds with the surrounding four other atoms in the crystal. A two-dimensional representation of the crystal structure of silicon (or germanium) at 0 K is shown in Fig. 8.1(a). The band diagram of this material is shown in Fig. 8.1(b).

At 0 K, all the valence electrons of Si atoms are participating in covalent bonds and their energies constitute a band of energies called valence band. So, at 0 K, valence band is completely filled and conduction band is empty of electrons. The allowed band of energies above valence band is called conduction band. Suppose, if we raise the temperature of the semiconductor to some room temperature T K, at this temperature some of the electrons which are participating in covalent bonds and present in the top energy levels of valence band will take thermal energies. If the increase in thermal energy of electrons present in top energy

Figure 8.1 (a) Crystal structure of Si at 0 K; (b) Band diagram of Si at 0 K

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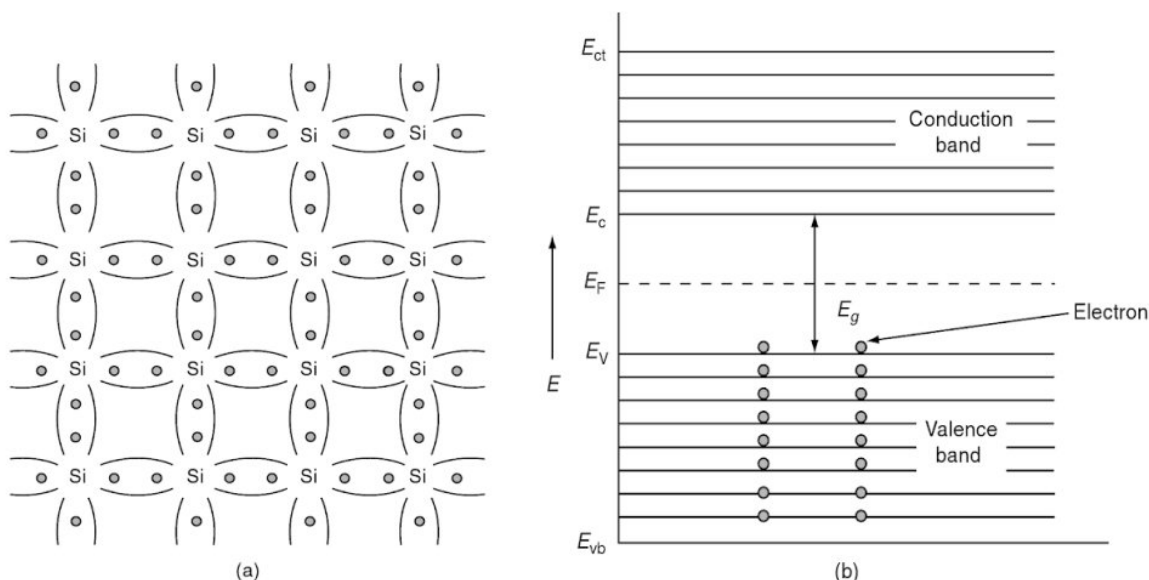
levels of valence band is equal to or greater than energy gap of the semiconductor, then electrons come away from bonding and move freely inside the crystal as shown in Fig. 8.2(a). Now these electrons possess energies equal to the lower energy levels of conduction band. These free electrons participate in electrical conduction, hence the band in which these electrons present is named as conduction band. If an electron comes away from bonding, then that atom acquires one unit positive charge, then it participates in electrical

Figure 8.2   (a) Crystal structure of Si at TK; (b) Band diagram of Si at TK
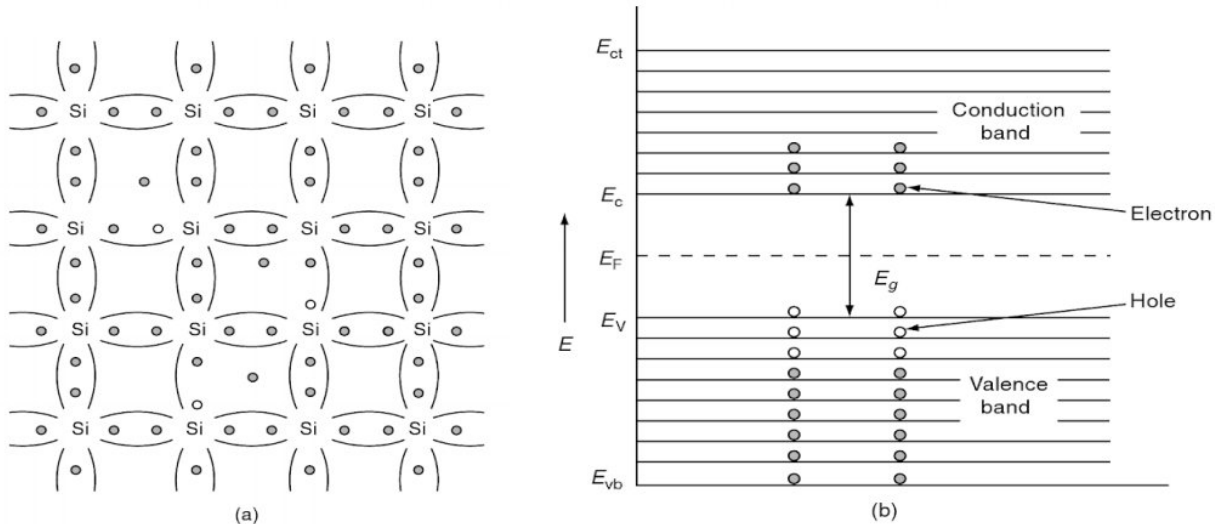
conduction. This electron vacancy or electron deficiency of an intrinsic semiconductor is called hole. The electron vacancies in valence band will exist as holes in the valence band as shown in Fig. 8.2(b).

Thus, at temperature TK, in an intrinsic semiconductor, if n covalent bonds are broken per unit volume of the material, then there will be n electrons in the conduction band and the same number of holes in the valence band. Usually, the number of free (or conduction) electrons present per unit volume of material, whose energies lie in the conduction band is called electron concentration and is represented as 'n'. Similarly, the number of holes present per unit volume of the semiconductor and in the valence band is called hole concentration represented as 'p'. Both the free electrons and holes present in the material participate in electrical conduction. The free electrons and holes present per unit volume of the material is called carrier concentration.

At some temperature TK, the free electron and hole concentration in an intrinsic semiconductor can be extracted in the following way:

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As Sunlight falling on the cell, some photons of the light are absorbed by solar cell. Some of the absorbed photons will have energy greater than the energy gap between valence band and conduction band in the semiconductor crystal. Hence, one valence electron gets energy from one photon and becomes excited and jumps out from the bond and creates one electron-hole pair. These electrons and holes of e-h pairs are called light-generated electrons and holes.

The light-generated electrons near the p-n junction are migrated to n-type side of the junction due to electrostatic force of the field across the junction. Similarly the light-generated holes created near the junction are migrated to p-type side of the junction due to same electrostatic force. In this way a potential difference established between two sides of the cell and if these two sides are connected by an external circuit current will start flowing from positive to negative terminal of the solar cell.

During choosing a particular solar cell for specific project it is essential to know the ratings of a solar panel. These parameters tell us how efficiently a solar cell can convert the light to electricity.

Short Circuit Current of Solar Cell

It is measured by short circuiting the terminals of the cell at most optimized condition of the cell for producing maximum output. The term optimized condition I used because for fixed exposed cell surface the rate of production of current in a solar cell also depends upon the intensity of light and the angle at which the light falls on the cell. As the current production also depends upon the surface area of the cell exposed to light, it is better to express maximum current density instead maximum current. Maximum current density or short circuit current density rating is nothing but ration of maximum or short circuit current to exposed surface area of the cell.

$$J_{sc} = \frac{I_{sc}}{A}$$

Where, I_{sc} is short circuit current, J_{sc} maximum current density and A is the area of solar cell.

Open Circuit Voltage of Solar Cell

It is measured by measuring voltage across the terminals of the cell when no load is connected to the cell. This voltage depends upon the techniques of manufacturing and temperature but not fairly on the intensity of light and area of exposed surface. Normally open circuit voltage of solar cell nearly equal to 0.5 to 0.6 volt. It is normally denoted by V_{oc}.

Maximum Power Point of Solar Cell

The maximum electrical power one solar cell can deliver at its standard test condition. If we draw the v-i characteristics of a solar cell maximum power will occur at the bend point of the characteristic curve. It is shown in the v-i characteristics of solar cell by P_m.

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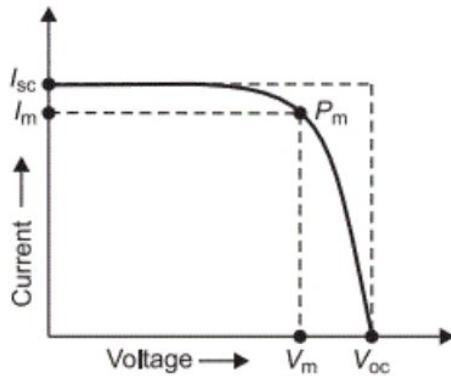
Current at Maximum Power Point

Current at Maximum Power Point is shown in the v-i characteristics of solar cell by I_m.

Voltage at Maximum Power Point

Voltage at Maximum Power Point is shown in the v-i characteristics of solar cell by V_m.

Fill Factor of Solar Cell

The ratio between product of current and voltage at maximum power point to the product of short circuit current and open circuit voltage of the solar cell.

$$Fill\ Factor = \frac{P_m}{I_{sc} \times V_{oc}}$$

Efficiency of Solar Cell

It is defined as the ratio of maximum electrical power output to the radiation power input to the cell and it is expressed in percentage. It is considered that the radiation power on the earth is about 1000 watt/square metre hence if the exposed surface area of the cell is A then total radiation power on the cell will be 1000 A watts. Hence the efficiency of a solar cell may be expressed as

$$Efficiency(\eta) = \frac{P_m}{P_{in}} \approx \frac{P_m}{1000A}$$

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LED - LIGHT EMITTING DIODE

On forward biasing a p-n diode, energy is given off in the form of heat in some diodes, while photons are emitted in addition to heat in some other diodes. A p-n diode specially prepared to produce visible and IR light on forward biasing is called light emitting diode. On forward biasing a LED, the majority carriers present in the respective regions of diode cross the p-n junction. The free electrons at the n-side move towards the p-side and holes at the p-side move towards the n-side of the diode. The free electrons that enter the p-side from the n-side are called minority carriers in the p-region and vice versa.

This increases the local minority carrier population than the normal value. This is known as minority carrier injection. The excess minority carriers diffuse away from the junction and produce recombinations with majority carriers. For example, the excess minority electrons in the conduction band of the p-region recombine with the majority holes in the valence band of the p-region and emit photons. Here the electrons make downward transition from conduction band to valence band for recombination with holes and the difference of energy will be emitted in the form of photons of energy E_g. Similar action takes place in the n-region also. Under reverse bias no photons are emitted. The above process has been shown with the energy band diagram shown in Fig. 8.30. The wave length of emitted photon in given by

$$\lambda = \frac{hc}{E_g} \qquad \text{———} \qquad (1)$$
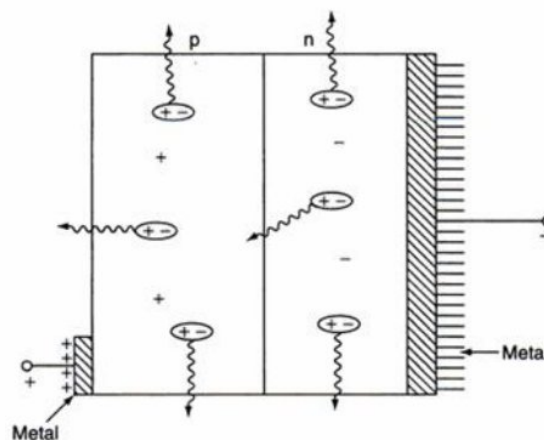
where h = Planck's constant = 6.626×10^{-34} Js.

Figure 8.30	Band diagram showing injection electroluminiscence in forward biased LED
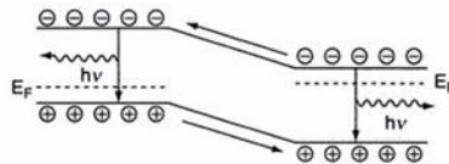
The basic structure of LED is shown in Fig. 8.31 (a), and its standard symbol in Fig. 8.31(b)

Figure 8.31	(a) Basic structure of LED

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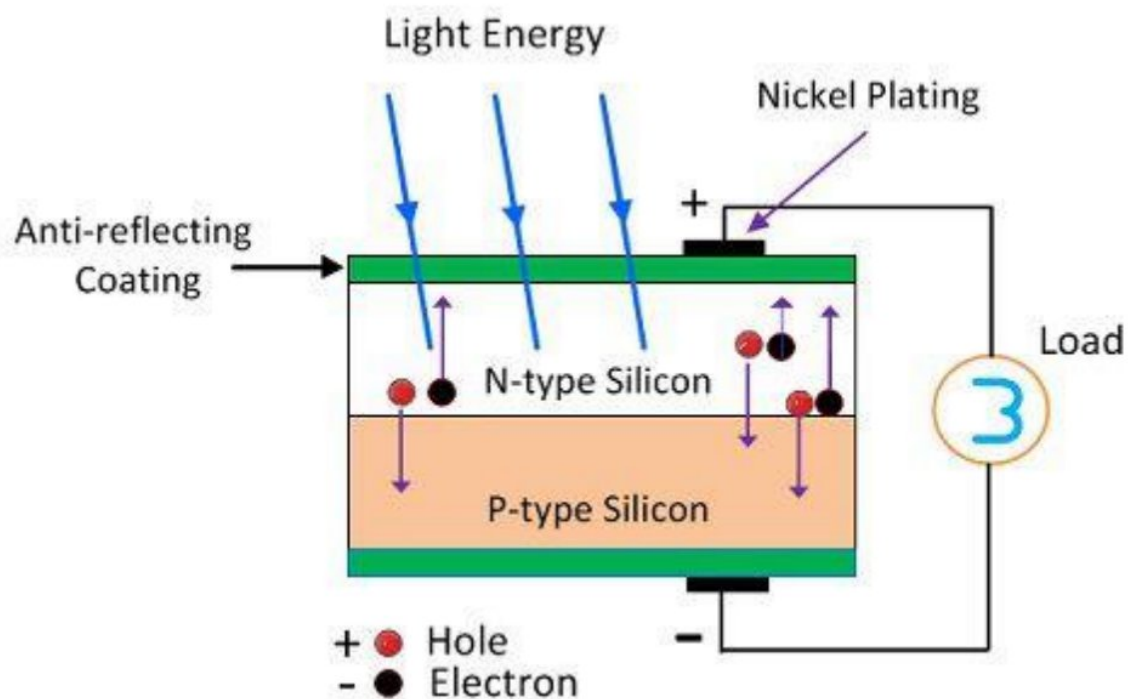CSE1

Figure 8. 31　　(b) Symbol of LED

The contact area of electrode on p-type material is smaller to permit the emergence of a large number of photons when the device is forward biased. The Si and Ge semiconductor diodes will not emit photons on forward biasing but heat is dissipated at the junction. The following table give the various LED materials and the colour of emitted waves.

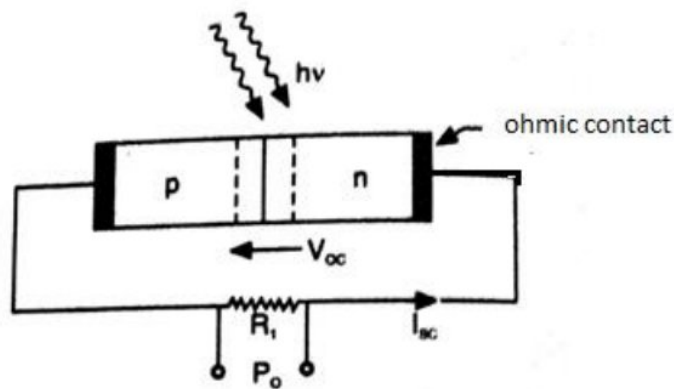## Table: Different LED materials in visible region

Material	Colour
GaP	Green
SiC	Blue
GaN	Blue
AlInGaP	Yellow
GaAsP [Direct band gap]	Red
GaAsP [Indirect band gap]	yellow

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SOLAR CELL

A solar cell is basically a p-n junction that can generate electrical power, when illuminated. Solar cells are usually large area devices typically illuminated with sunlight and are intended to convert the solar energy

Light Energy

Nickel Plating

Anti-reflecting Coating →

+

N-type Silicon

P-type Silicon

Load

3

+ ● Hole
− ● Electron

−

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Photons in sunlight hit the solar panel and are absorbed by semi-conducting materials. Electrons (-ve) are knocked loose from their atoms as they are excited. Due to their special structure and the materials in solar cells, the electrons are only allowed to move in a single direction. The electronic structure of the materials is very important for the process to work, and often silicon incorporating small amounts of boron or phosphorus is used in different layers. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity.

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Thermistor

 A thermistor is made from a semiconductor material. It is shaped into a disc, a rod or a bead. Bead thermistors may be only a few millimetres in diameter. Some bead thermistors have the bead enclosed in a glass capsule. Thermistor means thermally variable resistor.

Thermistor is special type of resistor, whose resistance varies more significantly with temperature than in standard resistors. Generally, the resistance increases with the temperature for most of the metals but the thermistors respond negatively i.e. the resistance of the thermistors decrease with the increase in temperature. This is the main principle behind thermistor. As the resistance of thermistors depends on the temperature, they can be connected in the electrical circuit to measure the temperature of the body.

The symbol of Thermistors can be represented as follows:
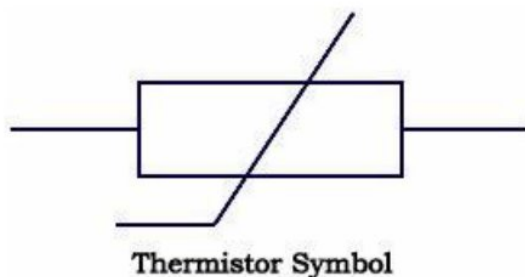
Thermistor Symbol

Types of Thermistors:

There are mainly 2 types of thermistors namely Positive-temperature coefficient (PTC) and Negative-temperature coefficient (NTC).

Positive Temperature Coefficient (PTC):

PTC thermistors increase their resistance as the temperature rises. The relationship between resistance and temperature is linear, as expressed in the following equation: deltaR = k(deltaT) where deltaR is the change in resistence, deltaT is the change in temperature and k is the temperature coefficient. When k is positive, it causes a linear increase in resistance as the temperature rises.

PTC Uses: PTC thermistors can be used in place of fuses for circuit protection. As the circuit heats up, resistance increases to prevent overload. They are also used as timing devices in televisions. When the unit is switched on, the degaussing coil is activated to eliminate the magnetic field; the thermistor automatically switches it off when the temperature reaches a certain point.

Negative Temperature Coefficient (NTC):

Many NTC thermistors are made from a pressed disc or cast chip of a semiconductor such as a sintered metal oxide. They work because raising the temperature of a semiconductor

increases the number of electrons able to move about and carry charge – it promotes them into the conduction band. The more charge carriers that are available, the more current a material can conduct. This is described in the formula:

I = n.A.v.e

Where

I = electric current (amperes)

n = density of charge carriers (count/m³)

A = cross-sectional area of the material (m²)

v = velocity of charge carriers (m/s)

e = charge of an electron ($e=1.602 \times 10^{-19}$ coulomb)

The current is measured using an ammeter. Over large changes in temperature, calibration is necessary. Over small changes in temperature, if the right semiconductor is used, the resistance of the material is linearly proportional to the temperature. There are many different semiconducting thermistors with a range from about 0.01 kelvin to 2,000 kelvins (-273.14 °C to 1,700 °C)

NTC Uses: NTC thermistors, on the other hand, are used as current-limiters and temperature monitors in digital thermostats and automobiles.

Thermistor characteristics:

As just mentioned above, resistance increase with increase in temperature for PTC and resistance decrease with increase in temperature for NTC.

The thermistor exhibits a highly non-linear characteristic of resistance vs temperature.
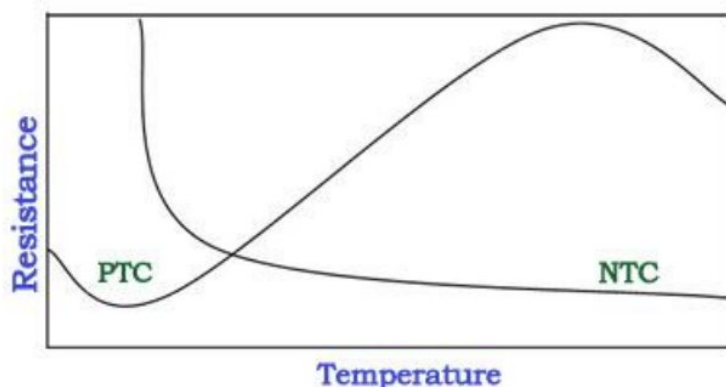
PTC thermistors can be used as heating elements in small temperature controlled ovens. NTC thermistors can be used as inrush current limiting devices in power supply circuits. Inrush current refers to maximum, instantaneous input current drawn by an electrical device when first turned on. Thermistors are available in variety of sizes and shapes; smallest in size are the beads with a diameter of 0.15mm to 1.25mm.

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There are two fundamental ways to change the temperature of thermistor internally or externally. The temperature of thermistor can be changed externally by changing the temperature of surrounding media and internally by self-heating resulting from a current flowing through the device.

The dependence of the resistance on temperature can be approximated by following equation,

$$R = R_0 e^{\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$ ------------------------------- (1) Where,

R is the resistance of thermistor at the temperature T (in K)
R0 is the resistance at given temperature T0 (in K)
β is the material specific-constant

The material specific-constant of a NTC thermistor is a measure of its resistance at one temperature compared to its resistance at a different temperature. Its value may be calculated by the formula shown below and is expressed in degrees Kelvin (°K).

Differentiating (1) with respect to T, we get
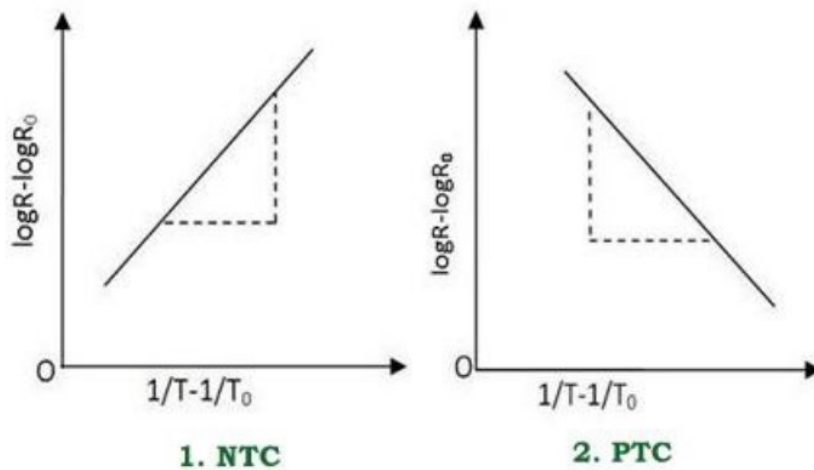
$$\frac{dR}{dT} = -\frac{R\beta}{T^2}$$

$$\alpha = -\frac{dR}{RdT}$$ is the temp coefficient of resistance.

Taking log of (1) and simplifying we get,

$$\beta = \frac{\log R - \log R_0}{\frac{1}{T} - \frac{1}{T_0}}$$ ------------------------------- (2)

so $$\alpha = -\frac{\beta}{T^2}$$ ------------------------------- (3)

A graph plotted with $\log R - \log R_0$ in Y axis and $\frac{1}{T} - \frac{1}{T_0}$ in X axis for NTC and PTC is shown below. The slope of graph gives value of β.

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1. NTC   **2. PTC**

Thermistor Applications:

- PTC thermistors were used as timers in the degaussing coil circuit of most CRT displays. A degaussing circuit using a PTC thermistor is simple, reliable (for its simplicity), and inexpensive.
- We can also use PTC thermistors as heater in automotive industry to provide additional heat inside cabin with diesel engine or to heat diesel in cold climatic conditions before engine injection.
- We can use PTC thermistors as current-limiting devices for circuit protection, as replacements for fuses.
- We can also use NTC thermistors to monitor the temperature of an incubator.
- Thermistors are also commonly used in modern digital thermostats and to monitor the temperature of battery packs while charging.
- We regularly use NTC thermistors in automotive applications.
- NTC thermistors are used in the Food Handling and Processing industry, especially for food storage systems and food preparation. Maintaining the correct temperature is critical to prevent food borne illness.
- NTC thermistors are used throughout the Consumer Appliance industry for measuring temperature. Toasters, coffee makers, refrigerators, freezers, hair dryers, etc. all rely on thermistors for proper temperature control.
- We can regularly use the Thermistors in the hot ends of 3D printers; they monitor the heat produced and allow the printer's control circuitry to keep a constant temperature for melting the plastic filament.
- NTC thermistors are used as resistance thermometers in low-temperature measurements of the order of 10 K.
- NTC thermistors can be used as inrush-current limiting devices in power supply circuits.

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HALL EFFECT

In 1879 E. H. Hall discovered that "if a metal or a semiconductor carrying a current I is subjected to a transverse magnetic field B, a potential difference V_H is produced in a direction normal to both the magnetic field and current directions." This is called *Hall Effect*. This effect established that it is negatively charged particles that carry current in metals.

Importance of Hall Effect

The importance of Hall Effect in the field of semiconductors is that it helps to determine the

- (*i*) type of semiconductor,
- (*ii*) sign of majority charge carriers,
- (*iii*) majority charge carrier concentration,
- (*iv*) mobility of majority charge carriers, and
- (*v*) mean drift velocity of majority charge carriers.

Experimental Arrangement

The experimental set up for the measurement of Hall voltage and determination of Hall coefficient is shown in Fig. 37.23 (*a*). A thin rectangular semiconductor wafer is mounted on
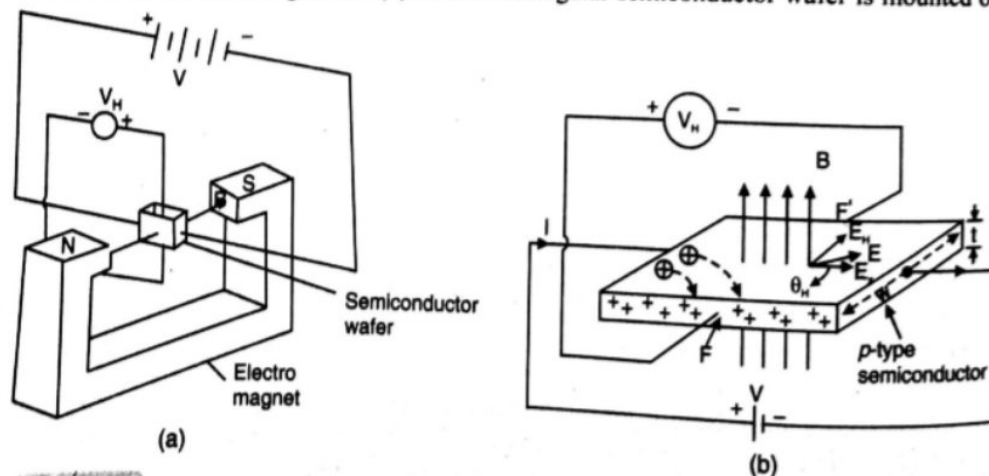
Fig. 37.23:

(a) Basic experimental arrangement to study Hall effect (b) Generation of Hall voltage

an insulating strip and two pairs of electrical contacts are provided on opposite sides of the wafer. One pair of contacts is connected to a constant current source. And the other pair is connected to a sensitive voltmeter. This arrangement is mounted in between two pole pieces of an electromagnet such that the magnetic field acts perpendicular to the lateral faces of the semiconductor wafer.

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Hall Voltage

Let us assume that the semiconductor is a p-type semiconductor. Let a potential difference V be applied across its ends. A current of strength I flows through it along the x-direction (Fig. 37.23 b). Holes are the majority charge carriers in the p-type semiconductor. The current through the wafer is given by

$$I = peAv_d \qquad\qquad ...(37.111)$$

where p is the hole concentration

A is the area of cross-section of the end face of semiconductor wafer,

e is the electrical charge associated with a hole, and

v_d is the average drift velocity of holes.

The current density $\qquad J_x = \dfrac{I}{A} = pev_d \qquad\qquad ...(37.112)$

Any plane perpendicular to the current flow direction is an equipotential surface. Therefore, the potential difference between the front and rear faces F and F' is zero (see Fig. 37.24).

Now, if a magnetic field B is applied normal to the wafer surface and hence to the direction of current flow in it, then a transverse potential difference is produced between faces F and F'. It is known as *Hall Voltage V_H*.

Fig. 37.24:

Top view of the wafer - The directions of magnetic force and Hall field in p-type semiconductor

Without the application of magnetic field, holes move parallel to faces F and F'. On application of magnetic field B, the holes experience a sideways deflection due to the magnetic force F_L, which is given by

$$F_L = eBv_d \qquad\qquad ...(37.113)$$

Holes are deflected toward the front face F and pile up there. Due to this, a corresponding equivalent negative charge is left on the rear face F'. These opposite charges produce a transverse electric field, E_H' whose direction is from the front to the rear face. Due to the action of E_H, holes experience an electric force in addition to the Lorentz force. When the force F_E due to this transverse electric field balances the magnetic force F_L, equilibrium condition is attained and the holes once again flow along x-direction parallel to the faces F and F'.
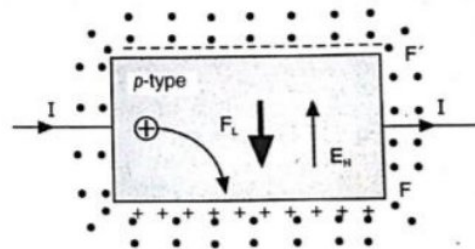
In the equilibrium condition

$$F_E = F_L$$

$$\therefore \qquad eE_H = ev_d B$$

If 'w' is the width of the semiconductor wafer, $E_H = \dfrac{V_H}{w}$

$$\therefore \qquad \left(\frac{V_H}{w}\right) = Bv_d \qquad\qquad ...(37.114)$$

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From Eq. (37.112), we have $\quad \upsilon_d = \dfrac{J_x}{pe}$

Therefore, we can write Eq. (37.114) as

$\therefore \qquad\qquad\qquad\qquad \dfrac{V_H}{w} = \dfrac{BJ_x}{pe}$ $\qquad\qquad\qquad$ ...(37.115)

$$V_H = \dfrac{wBJ_x}{pe} = \dfrac{wBI}{peA}$$

If 't' is the thickness of the semiconductor plate, $A = w\,t.$

$\therefore \qquad\qquad\qquad\qquad V_H = \dfrac{BI}{pet}$ $\qquad\qquad\qquad$ ...(37.116)

Hall Coefficient

Hall coefficient, R_H is defined as Hall field per unit current density per unit magnetic induction.

Thus, $\qquad\qquad\qquad\qquad R_H = \dfrac{E_H}{J_x B} = \dfrac{V_H / w}{J_x B}$

Using Eq. (37.114), we get

$$R_H = \dfrac{BJ_x}{peJ_x B}$$

or $\qquad\qquad\qquad\qquad R_H = \dfrac{1}{pe}$ $\qquad\qquad\qquad$ ...(37.117)

Hall voltage, V_H can now be written as

$\qquad\qquad\qquad\qquad V_H = R_H \dfrac{BI}{t}$ $\qquad\qquad\qquad$ ...(37.118)

$\therefore \qquad\qquad\qquad\qquad R_H = \dfrac{V_H t}{BI}$ $\qquad\qquad\qquad$ ...(37.119)

Eq. (37.119) is derived assuming that the p-semiconductor contains only holes. When the two types of charge carriers are taken into account, it is shown that the Hall coefficient is given by

$\qquad\qquad\qquad\qquad R_H = \dfrac{(p\mu_h^2 - n\mu_e^2)}{e(p\mu_h + n\mu_e)^2}$ $\qquad\qquad\qquad$ ...(37.120)

From the Eq. (37.120), we see that the Hall coefficient and Hall voltage are smaller for intrinsic materials than for extrinsic materials.

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