

Unit-IIISemiconductors

- **Contents**

Intrinsic semiconductors-Carrier concentration, dependence of Fermi level on Carrier - concentration and temperature, Extrinsic Semiconductors (Qualitative), Continuity equation - Carrier generation and recombination, Carrier transport: diffusion and drift currents, Hall Effect, Hall Experiment, Measurement of Hall mobility, Resistivity, carrier density using Hall effect.

- **WIT-WIL**

“Semiconductor” is a common word in technological world. Most of electronic equipment are made with semiconductors. To manufacture transistors, amplifiers LEDs, Laser diodes we use semiconductors. Conductivity will be changed when concentration changed in a semiconductor. Energy gap of semiconductor diode will decide the colour of output LED or laser diode. Here we study concentration of carriers in semiconductors and about Fermi level.

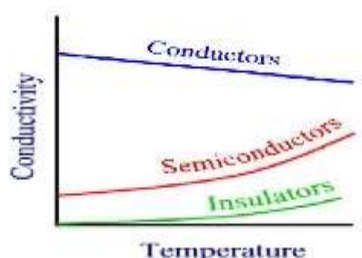
- **Introduction**

Certain substances like Germanium, Silicon, Carbon are neither good conductors like copper nor insulators like glass. In other words the resistivity of these materials lies in between conductors and Insulators. They are extensively used in electronic circuits. “A semi-conductor is a substance which has resistivity (10^{-4} to $0.5 \Omega \text{ m}$) in between Conductors and Insulators.

- **Characteristics of a Semi-Conductor**

The main features of pure semi-conductor are

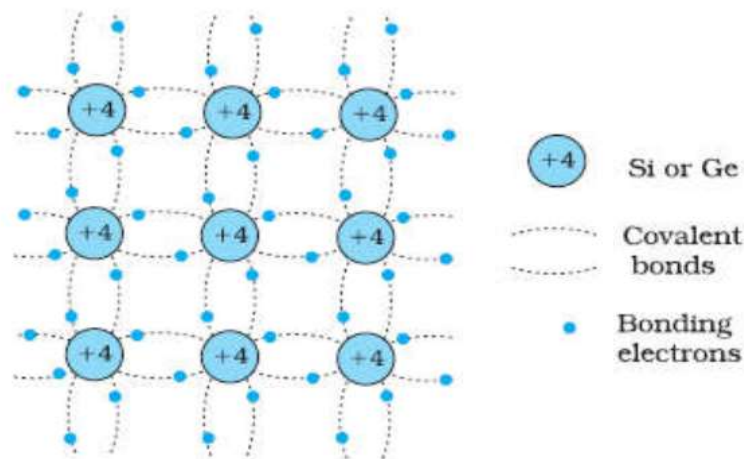
1. The resistivity of a semiconductor is more than metal conductor but less than insulators.
2. Semiconductors have negative temperature coefficient of resistance i.e the resistance of a semiconductor decreases with increase in temperature and vice-versa.



3. One of the most important characteristic is semi-conductor doping. It is the process of adding very small well controlled amounts of impurities into a semi-conductor. It enables the control of resistivity and other properties over a wide range of values.

• Bonds In Semi-Conductors

The best examples of semi-conductors are Ge, Si, Carbon, Selenium etc. There are four valence electrons in both Ge, Si. Such atoms do not usually gain (or) lose four valence electrons but share them with neighboring atoms. The union of atoms sharing the four valence electrons is called a covalent bond. These filled covalent bonds does not have the individual free electrons present in metal conductors. Thus semiconductors have much more high resistance than the conductors. The crystal structure forming covalent bonds make it possible to add impurities. The main idea of adding impurities is to alter Electrical Characteristics

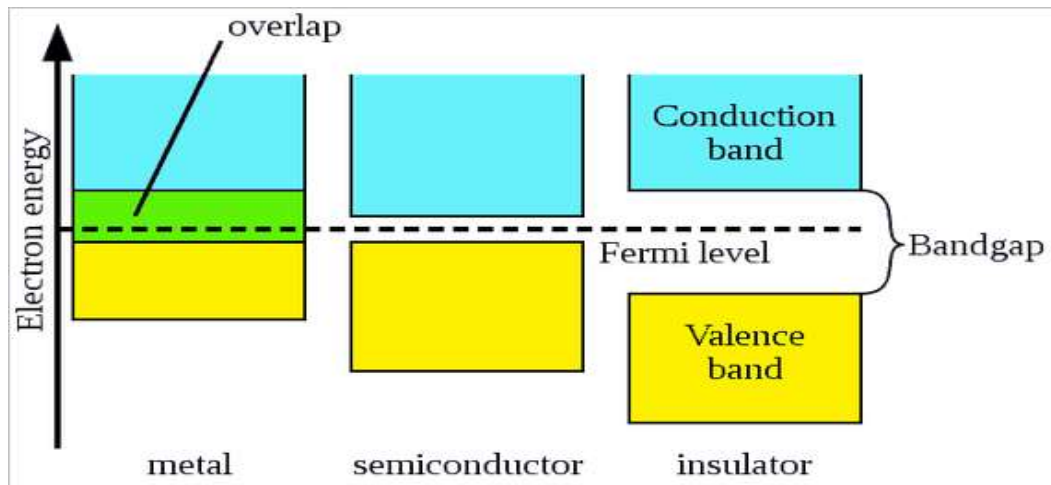


• Energy Band description of Semiconductor

In Semi-Conductors, the energy band is very narrow. The energy provided at room temperature is sufficient to lift the electrons from valence band to conduction band. Some electrons do jump the gap and go into the conduction band. Thus at room temperature semi-conductors are capable of conducting partial amount of current. Thus a semi-conductor has

- 1) A partially filled Conduction band
- 2) A partially filled Valence band

3) A very narrow energy gap ($\sim 1\text{eV}$) between them.



• Types of Semi-Conductors

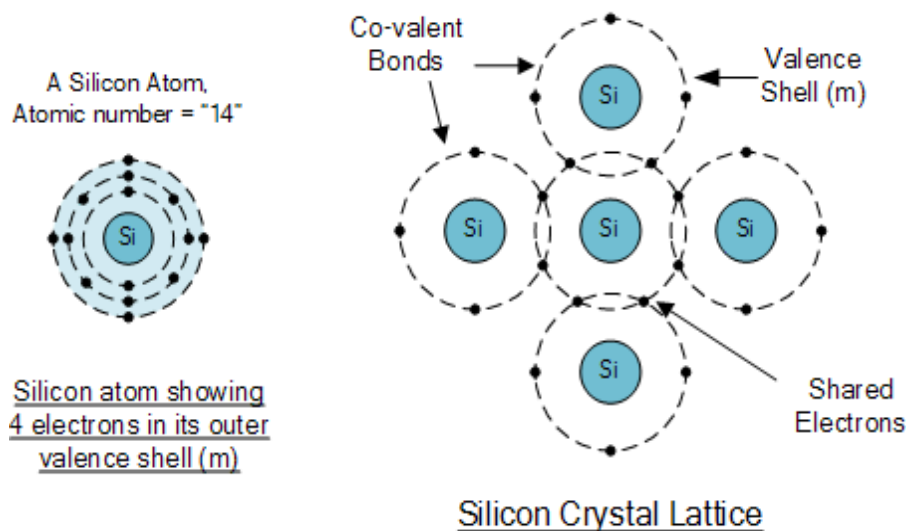
There are two types of Semi-Conductors

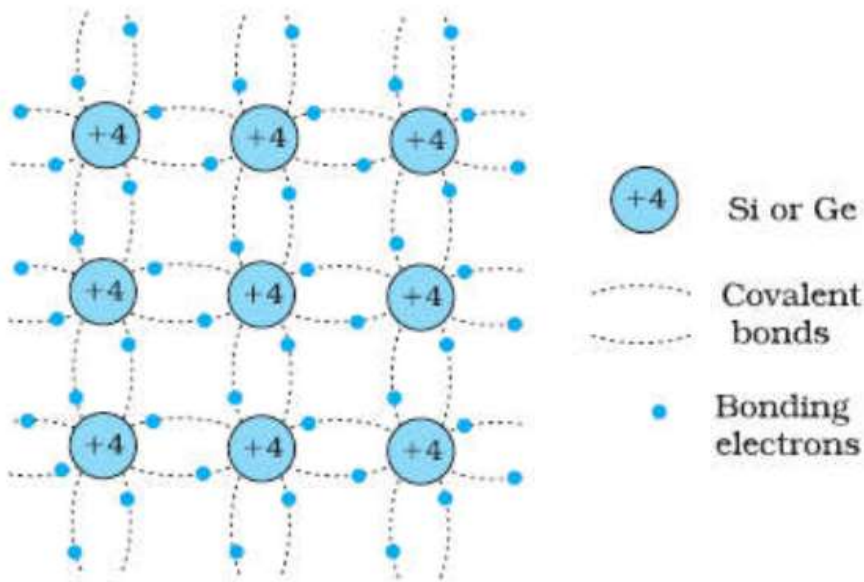
1) Intrinsic Semi-conductor 2) Extrinsic Semi-conductor

• Intrinsic Semi-Conductor

A semi-conductor in its natural pure form is called Intrinsic Semi-Conductor. The oxides of both Ge and Si are reduced chemically to produce the elements with 100% purity.

• Mechanism of Current Flow in Intrinsic Semi-Conductor





Consider energy band diagram of semi-conductor. At 0K, there are no electrons in conduction band and the valence band is completely filled, because all the electrons in valence band are tightly bound due to covalent bonding. At this temperature, the covalent bonds are very strong and there are no free electrons. Due to non-availability of electrons, the semi-conductor behaves as an Insulator.

When the temperature is raised, some of the covalent bonds in the semi conductor breaks due to the thermal energy supplied. The breaking of these bonds sets those electrons free which are engaged in the formulation of those bonds. These free electrons constitute tiny current when a potential difference is applied across the semi conductor crystal. As the temperature is raised, some of the valence electrons acquire sufficient energy to enter into the conduction band and thus become free electrons. Under the influence of electric field, these free electrons constitute electric current. Also when a valence electron jumps from valence band to conduction band, a hole is created in valence band. These holes also constitute current. The direction of hole current is same as conventional current but opposite to electron flow.

✓ **NOTE:** A hole has the same amount of positive charge equal to an electron but with opposite polarity. This will be present only in semi-conductors because of unfilled covalent bonds.

• Carrier Concentration In Intrinsic Semi-Conductor In Thermal Equilibrium

A semi-conductor in an extremely pure form is known as intrinsic semiconductor. In an intrinsic semiconductor at absolute zero, valence band is completely filled and conduction band is empty. Because of non-availability of electrons the semi conducting material behaves as an insulator. When temperature is raised above absolute zero, hole-electron pairs are created. The free electrons are produced due to the breaking up of some covalent bonds due to thermal energy. At the same time holes are created in covalent bonds. Under the influence of electric field, conduction through the semiconductor is by both free electrons and holes. Therefore the total current inside the semiconductor is the sum of currents due to free electrons and holes.

Let 1) Electrons in conduction band behave as the particles with an effective mass m_e

2) The number of conduction electrons per cubic meter whose energy lie between E and $E+dE$ is given by

$$dn_c = Z(E)f(E)dE \text{-----(1)}$$

where $Z(E) dE$ is the density of states in the energy interval E and $E+dE$ and $f(E)$ is the electron occupancy probability i.e the probability that a state of energy E is occupied by an electron.

Here

$$Z(E) = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} \text{-----(2)}$$

Where m_e^* is the effective mass of electron.

$$f(E) = \frac{1}{1 + e^{\frac{(E-E_f)}{kT}}} \text{----- (3)}$$

where K =Boltzmann Constant, T =Temperature in Kelvin, E_f = Fermi level.

For possible temperatures ; $E-E_f \gg kT$ hence above equation can be written as

$$f(E) = \frac{1}{e^{\frac{(E-E_f)}{kT}}} = e^{\frac{-(E-E_f)}{kT}} = e^{\frac{(E_f-E)}{kT}} \text{----- (4)}$$

The electrons in conduction band are having energies lying from E_c to ∞ while the electrons in valence band have energies lying from $-\infty$ to E_v .

The concentration of electrons in the conduction band is given by

$$n_c = \int_{E_c}^{\infty} Z(E)f(E)dE \text{-----(5)}$$

where E_c is the energy at the bottom of conduction band.

Combining (2),(4),(5) then the density of electrons in conduction band is

$$n_c = \int_{E_c}^{\infty} \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} \exp\left(\frac{E_f - E}{kT}\right) dE$$

$$n_c = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} \exp\left(\frac{E_f - E}{kT}\right) dE$$

$$n_c = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \exp\left(\frac{E_f}{kT}\right) \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} \exp\left(\frac{-E}{kT}\right) dE \text{ --- (6)}$$

To solve this integral let us put

$$E - E_c = x$$

$$E = E_c + x$$

$$dE = dx$$

$$n_c = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \exp\left(\frac{E_f}{kT}\right) \int_0^{\infty} (x)^{\frac{1}{2}} \exp\left(\frac{-(E_c + x)}{kT}\right) dx$$

$$n_c = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \exp\left(\frac{E_f - E_c}{kT}\right) \int_0^{\infty} (x)^{\frac{1}{2}} \exp\left(\frac{-x}{kT}\right) dx \text{ --- (7)}$$

Using gamma function it can be shown that

$$\int_0^{\infty} (x)^{\frac{1}{2}} \exp\left(\frac{-x}{kT}\right) dx = (kT)^{\frac{3}{2}} \frac{\pi^{\frac{1}{2}}}{2}$$

Hence, the equation (7) can be written as

$$n_c = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \exp\left(\frac{E_f - E_c}{kT}\right) (kT)^{\frac{3}{2}} \frac{\pi^{\frac{1}{2}}}{2}$$

i.e the number of electrons per unit volume of the material is given by

$$n_c = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} \exp\left(\frac{E_f - E_c}{kT}\right)$$

Calculation of density of holes:

Let dp be the number of holes in energy interval E and $E+dE$ in the valance band

$$dp = Z(E) (1 - f(E)) dE \text{ --- (1)}$$

where $N(E) dE$ is the density of states in the energy interval E and $E+dE$ and $(1-f(E))$ is the hole (absence of electron) occupancy probability i.e the probability that a state of energy E is occupied by a hole.

Here

$$N(E) = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}} \quad \text{--- (2)}$$

Where m_h^* is the effective mass of hole.

$$1 - f(E) = \left(1 - \frac{1}{1 + e^{\frac{(E-E_f)}{kT}}}\right) \quad \text{--- (3)}$$

where K =Boltzmann Constant, T =Temperature in Kelvin, E_f = Fermi level.

For possible temperatures ; $E-E_f \gg kT$ hence above equation can be written as

$$1 - f(E) = e^{-\frac{(E-E_f)}{kT}} \quad \text{--- (4)}$$

The holes in valance band are having energies lying from $-\infty$ to E_v

The concentration of holes in the valance band is given by

$$p_v = \int_{-\infty}^{E_v} N(E)(1 - f(E))dE \quad \text{--- (5)}$$

where E_v is the energy at the highest level of valance band.

Combining (2),(4),(5) then the density of holes in valance band is

$$\begin{aligned} p_v &= \int_{-\infty}^{E_v} \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}} \exp\left(\frac{E - E_f}{kT}\right) dE \\ p_v &= \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} \exp\left(\frac{E - E_f}{kT}\right) dE \\ p_v &= \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} \exp\left(\frac{-E_f}{kT}\right) \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} \exp\left(\frac{E}{kT}\right) dE \quad \text{--- (6)} \end{aligned}$$

To solve this integral let us put

$$E_v - E = x$$

$$E = E_v - x$$

$$dE = -dx$$

$$\int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} \exp\left(\frac{E}{kT}\right) dE = \int_{\infty}^0 x^{\frac{1}{2}} \exp\left(\frac{E_v - x}{kT}\right) (-dx)$$

$$p_v = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} \exp\left(\frac{-E_f}{kT}\right) \int_{\infty}^0 x^{\frac{1}{2}} \exp\left(\frac{E_v - x}{kT}\right) (-dx)$$

$$p_v = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} \exp\left(\frac{E_v - E_f}{kT}\right) \int_0^{\infty} x^{\frac{1}{2}} \exp\left(\frac{-x}{kT}\right) (dx) \text{ --- (7)}$$

Using gamma function it can be shown that

$$\int_0^{\infty} (x)^{\frac{1}{2}} \exp\left(\frac{-x}{kT}\right) dx = (kT)^{\frac{3}{2}} \frac{\pi^{\frac{1}{2}}}{2}$$

Hence, the equation (7) can be written as

$$p_v = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} \exp\left(\frac{E_v - E_f}{kT}\right) (kT)^{\frac{3}{2}} \frac{\pi^{\frac{1}{2}}}{2}$$

i.e the number of holes per unit volume of the material is given by

$$p_v = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} \exp\left(\frac{E_v - E_f}{kT}\right)$$

Intrinsic carrier concentration:

In intrinsic semiconductors concentration of electrons and holes are equal

Hence, $n_c = p_v = n_i$ is called intrinsic carrier concentration.

Therefore

$$n_i^2 = n_c p_v = 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_h^* m_e^*)^{\frac{3}{2}} \exp\left(\frac{E_v - E_c}{kT}\right)$$

$$= 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_h^* m_e^*)^{\frac{3}{2}} \exp\left(\frac{-E_g}{kT}\right)$$

Where $E_c - E_v = E_g$ is the forbidden energy gap.

Hence

$$n_i = 2 \left(\frac{2\pi kT}{h^2} \right)^{\frac{3}{2}} (m_h^* m_e^*)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2kT}\right)$$

• Fermi level in intrinsic semiconductor:

In intrinsic semiconductors concentration of electrons and holes are equal

Hence, $n_c = p_v$, using the above equations,

$$2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp \left(\frac{E_f - E_c}{kT} \right) = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp \left(\frac{E_v - E_f}{kT} \right)$$

$$(m_e^*)^{3/2} \exp \left(\frac{E_f - E_c}{kT} \right) = (m_h^*)^{3/2} \exp \left(\frac{E_v - E_f}{kT} \right)$$

$$\exp \left(\frac{2E_f}{kT} \right) = \left(\frac{m_h^*}{m_e^*} \right)^{3/2} \exp \left(\frac{E_v + E_c}{kT} \right)$$

Taking logarithms on both sides

$$\left(\frac{2E_f}{kT} \right) = \frac{3}{2} \ln \frac{m_h^*}{m_e^*} + \left(\frac{E_v + E_c}{kT} \right)$$

i.e.,

$$E_f = \frac{3kT}{4} \ln \frac{m_h^*}{m_e^*} + \left(\frac{E_v + E_c}{2} \right) \text{ --- (1)}$$

if we assume that $m_e^* = m_h^*$

$$E_f = \frac{E_v + E_c}{2} \text{ --- (2)}$$

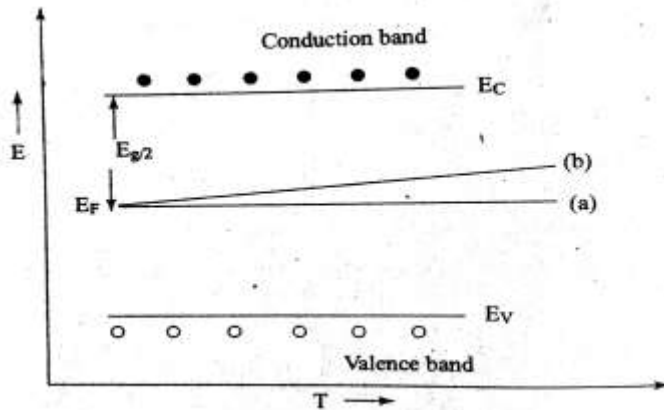


Figure: Temperature dependence of Fermi level in intrinsic semiconductor

(a): at $T=0K$ (b): $T>0K$ and $m_h^* > m_e^*$

Thus Fermi level is located half way between the valance and conduction bands and its position is independent of temperature. Since m_h^* is greater than m_e^* , E_f is just above the middle, and rises slightly with increasing temperature as shown in above figure.

• **Carrier concentration in extrinsic semiconductor:**

As already mentioned the carrier concentration and hence the conductivity can be enhanced many orders in semiconductor by doping technology. Depending on the nature of the impurities majority charge carriers may be free electrons as in the n-type (or) holes as in the p-type semiconductor.

Suppose the doped atoms are donors (n-type) so that free electron concentration n_c is increased to $n = k n_i$, $k > 1$. The hole concentration p_v ($= n_i$ before doping) decreases in the same proportion to $p = p_i/k$ as we have seen that in any type of semiconductor.

$$n.p = \text{constant, at a given temperature}$$

total concentration is,

$$n_c + p_v = 2n_i = 2p_i \text{ before doing}$$

then after doping

$$n + p = k n_i + p_i/k = (k + 1/k) n_i$$

in intrinsic $n_c = p_v = n_i$

$$(k + 1/k) n_i > 2 n_i \text{ since } k > 1$$

Here the decreased number of holes is less than added number of electrons.

From the above equations. By proper doping number of charge carriers increased and then conductivity also increases.

Temperature dependence of Fermi level in N-type semiconductor:

In energy level diagram of n-type semiconductor, E_d is the donor energy level. At low temperatures number of electrons in conduction band must be equal to number of donors. By taking this into consideration and solve the equation. Then,

$$E_f = \left(\frac{E_c + E_d}{2} \right) + \frac{kT}{2} \log \left(\frac{N_d}{2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2}} \right)$$

At $T=0K$

$$E_f = \left(\frac{E_c + E_d}{2} \right)$$

i.e., at 0K Fermi level lies exactly middle of the donor level and bottom of conduction band E_c . As 'T' increases Fermi level moves downward and behaves as intrinsic semiconductor at high temperatures as shown in below figure.

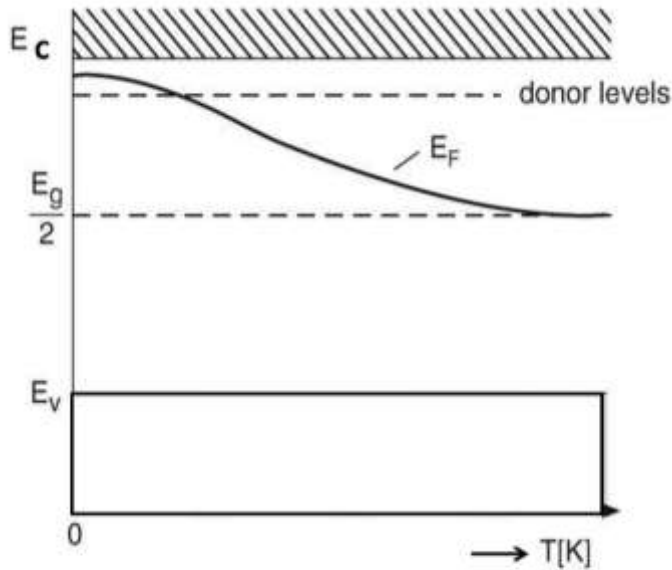


Figure: Temperature dependence of Fermi level in N-type semiconductor

Temperature dependence of Fermi level in P-type semiconductor:

In energy level diagram of P-type, E_a is the acceptor energy level. At low temperature density of holes in valance band is equal to density of ionized acceptors. When the calculation done based on this the final equation will be

$$E_f = \left(\frac{E_c + E_a}{2} \right) - \frac{kT}{2} \log \left(\frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right)$$

At 0K

$$E_f = \left(\frac{E_c + E_a}{2} \right)$$

i.e at 0K Fermi level lies exactly middle of E_v and E_a as temperature increases, it moves upward and behaves like intrinsic at high temperature as shown here.

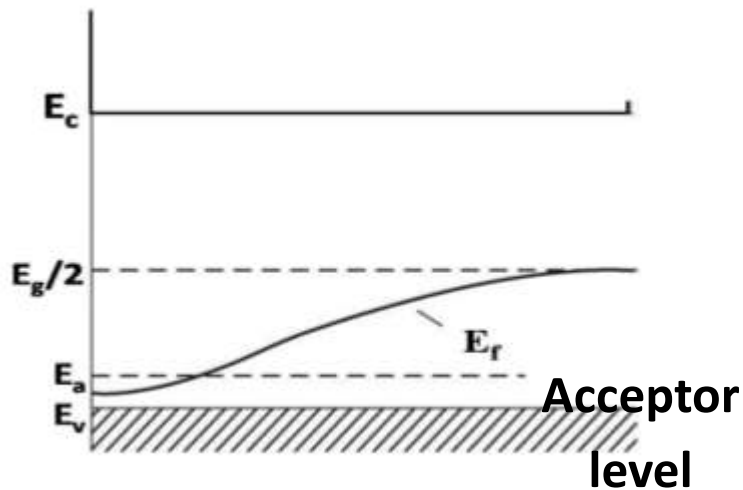


Figure: Temperature dependence of Fermi level in P-Type Semiconductor

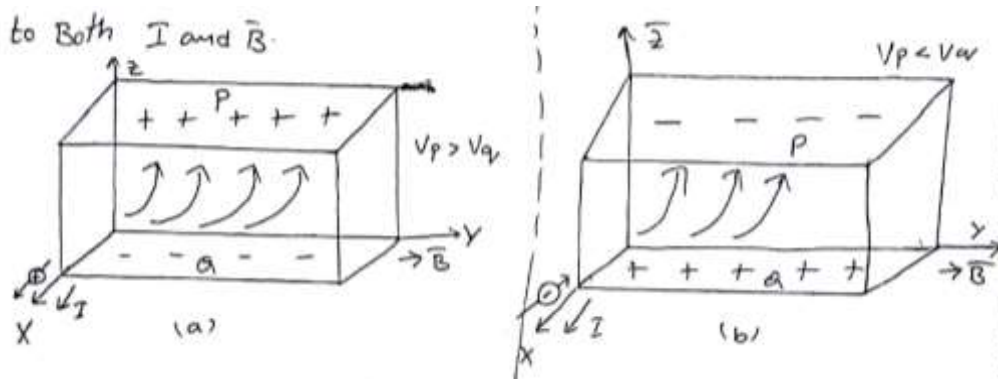
- **Hall Effect:**

“When a current-carrying semiconductor is kept in a magnetic field, the charge carriers of the semiconductor experience a force in a direction perpendicular to both the magnetic field and the current. At equilibrium, a voltage appears at the semiconductor edges.”

In semiconductor it is not possible to assert the sign of charges from the direction of the external current because it is the same whether positive charge flow in that direction (or) negative charge flow in opposite direction.

Hall effect, discovered by E.H Hall in 1879, helps to resolve the dilemma on sign of the charges. It is the following experiment result.

When slab carrying current ‘I’ is kept in transverse magnetic field (B), a potential difference will develop along a direction perpendicular to both I and B.



Consider a rectangular slab carrying current 'I' in X-direction. if place it in a magnetic field B which is in the Y-direction, a potential difference V_{pq} will develop between the faces P and Q which are perpendicular to Z-direction.

This effect on charge carriers due to magnetic field force. This can be written as, $q(\vec{V} \times \vec{B})$, where 'q' is charge.

The charges initially drifting such that the current 'I' is along the X-direction, will be deflected along Z-direction under the action of force due to magnetic field.

If the charges responsible for I are positive, they will deflect towards P surface as shown in figure (a) and potential V_p at P will be greater than potential V_q at Q.

If they are negative, then they will drift in opposite direction of I, they will also deflect towards 'P' as shown in figure (b) then V_p will be lower than V_q .

Thus the sign of $V_{pq} = V_p - V_q = V_H$ will determine the sign of the current carrying charges ' V_{pq} ' is called "Hall voltage".

The corresponding electric field is called "Hall electric field (E_H)". which is perpendicular to 'V' and B plane.

$$E_H = \frac{V_{pq}}{d} \text{ --- (1)}$$

Where 'd' is the spacing between surfaces P and Q.

E_H will oppose the sideways deflection of the charges. Eventually, at equilibrium is reached further deflection of charges prevented.

This condition occurs when,

$$q\vec{E}_H + q(\vec{V} \times \vec{B}) = 0 \text{ --- (2)}$$

$$\vec{E}_H = -\vec{V} \cdot \vec{B} \sin \theta$$

where 'θ' is angle between V and B i.e 90°.

$$\bar{V} = -\frac{\bar{E}_H}{\bar{B}} \text{---(3)}$$

Further current is due to electrons, we have.

$$j = ne\bar{V} \text{---(4)}$$

Substitute (3) in (4), then

$$j = -ne\frac{\bar{E}_H}{\bar{B}}$$

$$\frac{\bar{E}_H}{j\bar{B}} = -\frac{1}{ne} = R_H$$

Where ‘ R_H ’ is called Hall coefficient.

We can write , $R_H = -\frac{1}{ne}$ for electrons, $R_H = \frac{1}{ne}$ for holes.

• Applications of Hall Effect:

(a) To measure type of semiconductor:

If Hall coefficient is Positive then it is P- type semiconductor, if it is negative then it is N-type semiconductor.

(b) To measure concentration of charge carriers:

We know that Hall coefficient can be written as

$$R_H = \frac{1}{ne}$$

$$n = \frac{1}{R_H e}$$

Concentration of charge carriers can be measured by Hall coefficient.

(c) To measure mobility of charge carriers:

We know that Conductivity can be written as

$$\sigma = ne\mu$$

$$\mu = \frac{\sigma}{ne} = \sigma R_H$$

Using conductivity and Hall coefficient mobility can be measured.

(d) To measure magnetic flux density:

Using a semiconductor sample of known R_H the magnetic flux can be measured by following formula. 15

$$B = \frac{V_H \cdot t}{R_H I}$$

Questions:

1. Obtain expression for concentration of charge carriers in intrinsic semiconductor.
2. Explain the variation of Fermi level with temperature in intrinsic semiconductor?
3. Discuss the carrier concentration in extrinsic semiconductors?
4. What is Hall effect? Obtain expression for Hall coefficient?
5. Mention the applications of Hall effect?
