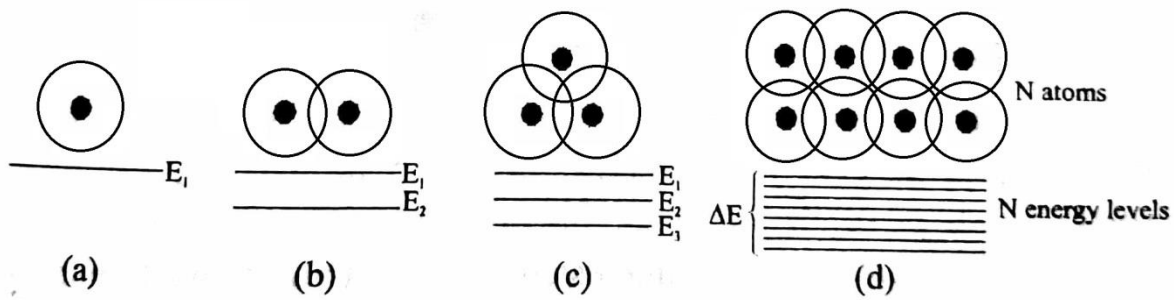# UNIT-IV

Formation of Energy bands in solids.

In an isolated atom the electrons are tightly bound and have discrete and sharp energy levels. When two identical atoms brought together then outermost orbit of these electrons overlap and interact. Therefore the energy of a particular electron is not unique rather two energies which are very close to each other. Similarly when more atoms are close to each other, then a particular electron is having a number of energies which are very close to each other. Hence instead of a sharp discrete energy this electron is having a band of energy. Generally this happens in case of a solid which consists of a number of atoms which are very close to each other.

The band corresponding to the outermost orbit is called conduction band. The next inner band is known as valence band. The gap between two allowed bands is known as forbidden energy gap or band energy.

Classification of solids based on Energy Bands

On the basis of energy bands solids are classified into Conductors,, Semiconductors, and Insulators.
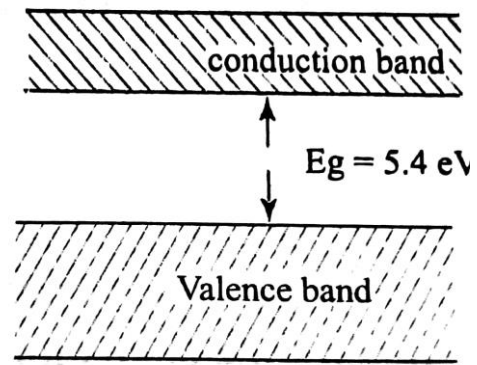
Conductor
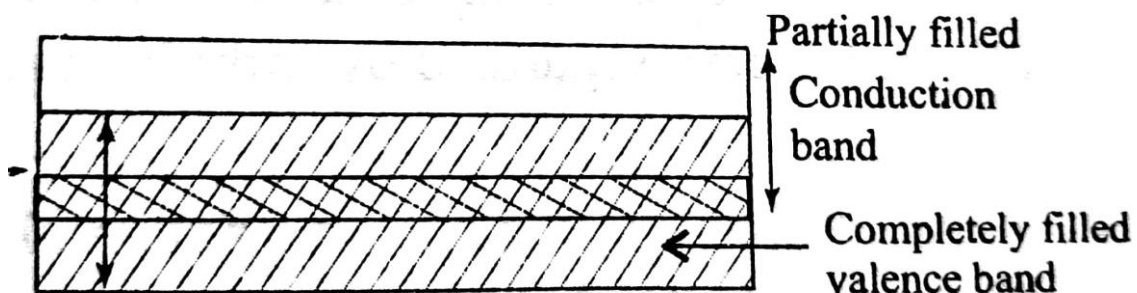
In case of conductor the conduction and valence bands overlap each other. Hence, electrons can easily move from the valence to the conduction band even at room temperature and without application of external energy. This makes availability of a large number of electrons for conduction. Also, the resistivity of such solids is low or the conductivity is high.

Insulators

In case of insulator the energy gap (E_g) is very large (>3 eV). Due to this large gap, electrons cannot be excited to move from the valence to the conduction band by thermal excitation. Hence, there are no free electrons in the conduction band and no conductivity.

conduction band

$Eg = 5.4\ eV$

Valence band

Diamond (insulator)

Semiconductors:

In semiconductor the energy gap is small (< 3 eV). Since the gap is small, some electrons acquire enough energy even at room temperature and enter the conduction band. These electrons can move in the conduction band increasing the conductivity of the solid. The resistivity of semiconductors is lower than that of insulators but higher than that of conductors.

conduction band

$Eg = 1.1\ eV$

Valence band
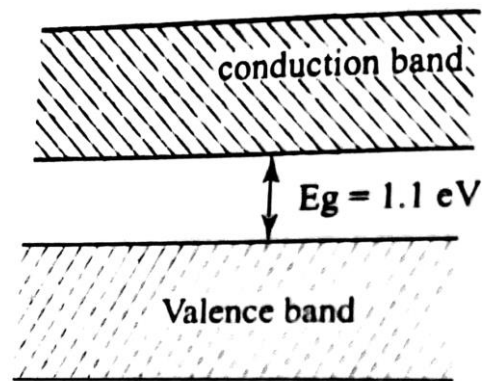
Silicon (semiconductor)

Fermi Level

According to fermi Dirac statistics the probability of an electron F(E) occupying an energy level E is given by

$$F(E) = \cfrac{1}{1+e^{\frac{E-E_F}{kT}}}, \qquad \text{Where } E_F \text{ is the fermi energy and F(E) is called fermi function.}$$

It is observed that at 0^0K all the energy state below the Fermi level are fully occupied and all the energy levels above the fermi level are empty.
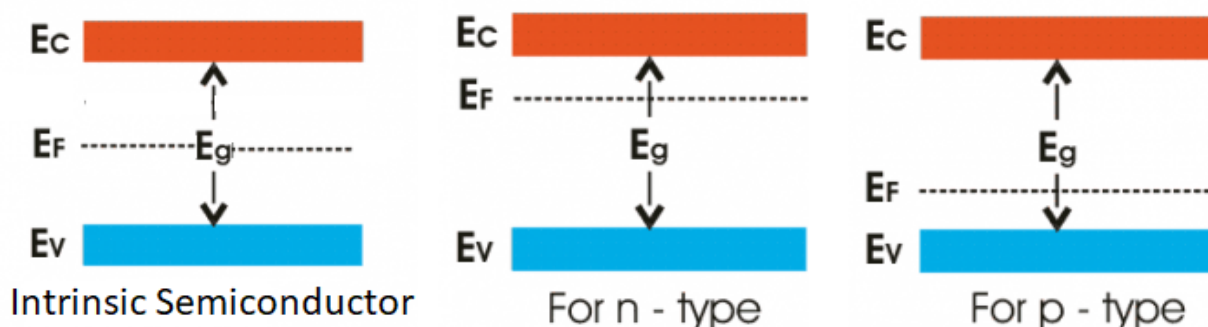
So Fermi level can be defined as the level of maximum energy of the filled state at 0^0K

If $E = E_F$ then $F(E) = \frac{1}{2}$

So the fermi level is defined as the energy level at which the probability of electron occupation is ½ at any other temperature above 0^0K

Fermi Energy

Fermi energy is the energy of that state where the probability of electron occupation is ½ at any other temperature above 0^0K. It can also be defined as the maximum energy of filled state at 0^0K

E_C E_F --------- E_g ------------ E_V
Intrinsic Semiconductor

E_C E_F ----------------- E_g E_V
For n - type

E_C E_g E_F ---------------- E_V
For p - type

SEMICONDUCTORS

Those substances whose electrical conductivity lies between conductor and insulator are known as semiconductors.e.g. germanium and silicon are important semiconductors which are vastly used in the manufacturing of semiconductor devices, GaAs (gallium arsenide) and InSb (indium antimonite), etc.

Properties:

- Semiconductors are tetravalent atoms.
- Conductivity increases with increasing temperature.
- Conductivity is due to holes and electrons.
- Forbidden energy gap is less than insulators.
- In a solid the bond between the atoms is covalent bond.

Types of semiconductors:

There are two types of semiconductors

1. Intrinsic semiconductors,
2. Extrinsic semiconductors.

Intrinsic semiconductors:

The semiconductor in purest form is known as intrinsic semiconductors.

Example: Pure germanium & silicon crystals.

Extrinsic semiconductors:

When a pure semiconductor is doped with suitable doping impurity is known as extrinsic semiconductors.

Example: doped germanium and silicon.

Depending on the type of impurity added, the extrinsic semiconductors can be divided in to two classes:
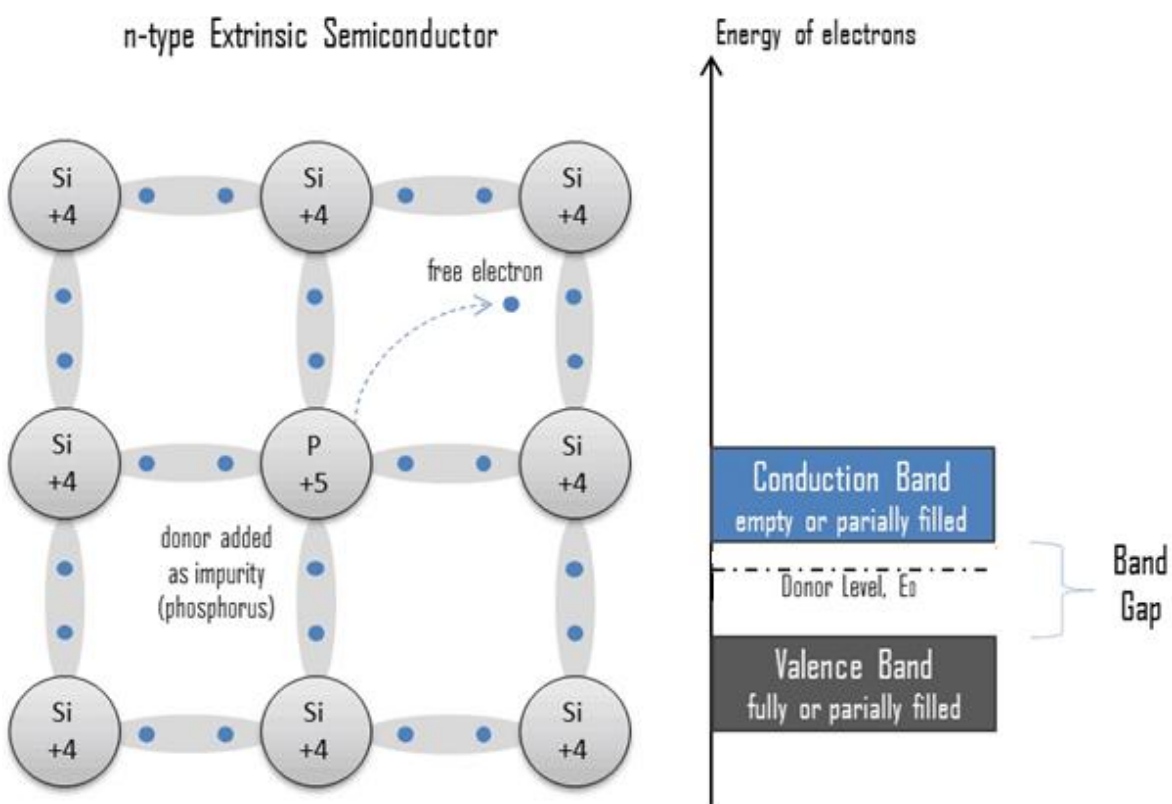
1. N-type Semiconductors
2. P-type Semiconductors

N-Type Semiconductor: When a group V dopants (pentavalent elements such as antimony, arsenic or phosphorous) is doped with a intrinsic semiconductor, an extrinsic semiconductor is formed. These pentavalent elements are called donor elements. A pentavalent atom is having five electron in their outermost orbit. When this atom is doped to a pure semiconductor like Ge or Si which are having four outermost orbit electron, then four electrons of the pentavalent atom formed four covalent bond with four electrons of Ge or Si atom. The fifth electron is free which helps the conduction of current. If a small amount of pentavalent substance is doped then a number of free electrons will be available for conduction of current which increases the conductivity of the semiconductor.

In an n-type semiconductor, the majority carrier, or the more abundant charge carrier, is the electron, and the minority carrier, or the less abundant charge carrier, is the hole.

Explanation

The increase in conductivity of an extrinsic semiconductor can be explained by energy band diagram shown in figure. When donor impurities are added to an intrinsic semiconductor, allowable energy levels (donor energy level) are introduced at a very small gap below the conduction band where the donor free electrons accommodate as illustrated in figure. These donor levels are essentially a discrete level because the added impurity atoms are far apart in the crystal structure and hence their interaction is small. In the case of Silicon, the gap of the new discrete allowable energy level is only 0.05 eV (0.01 eV for germanium) below the conduction band, and therefore at room temperature almost all of the "fifth" electrons of the donor impurity are raised into the conduction band and the conductivity of the material increases considerable.
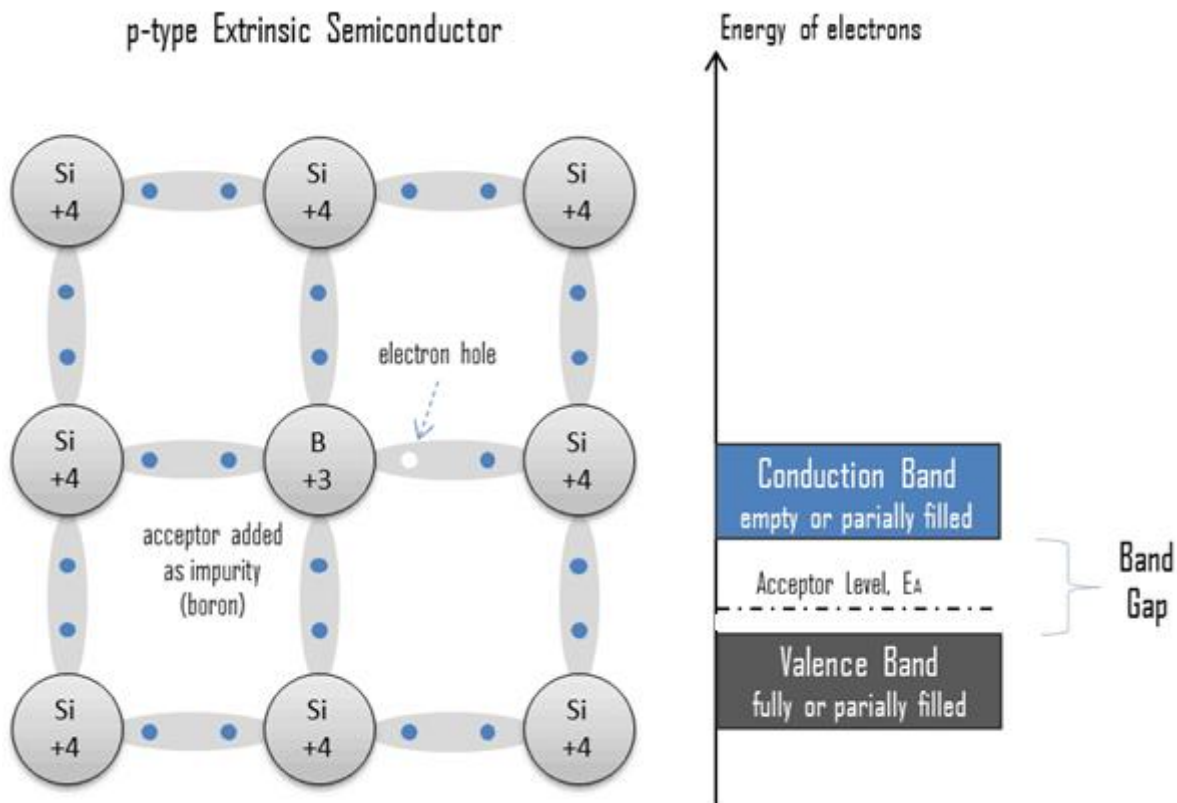

P-Type Semiconductor:

When a group III dopants (trivalent elements such as boron, aluminium or gallium) is doped with a intrinsic semiconductor, P-type semiconductor is formed. These trivalent elements are called acceptor elements. A trivalent atom is having three electron in their outermost orbit. When this atom is doped to a pure semiconductor like Ge or Si which are having four outermost orbit electron, then three electrons of the trivalent atom formed three covalent bond with three electrons of Ge or Si atom. The fourth electron of the parent atom did not get any electron from doped atom to form a covalent bond. This create a hole which is nothing but deficiency of an electron. If a small amount of trivalent substance is doped then a number of holes will be available for conduction of current which increases the conductivity of the semiconductor.

In an P-type semiconductor, the majority carrier, or the more abundant charge carrier, is the hole, and the minority carrier, or the less abundant charge carrier, is the electron.

Explanation

The increase in conductivity of an P-type semiconductor can be explained by energy band diagram shown in figure. When acceptor impurities are added to an intrinsic semiconductor, allowable discrete energy levels (acceptor energy level) are formed just above the valance band, as shown in figure. Since a very small amount of energy (0.08 eV in case of Silicon and 0.01 eV in case of Germanium) is required for an electron to leave the valence band and occupy the accepter energy level, holes are created in the valence band by these electrons.

Difference Between Intrinsic and Extrinsic Semiconductor

Intrinsic Semiconductors	Extrinsic Semiconductors
1 It is pure semi-conducting material and no impurity atoms are added to it.	1. It is prepared by doping a small quantity of impurity atoms to the pure semi-conducting material.
2 Examples: crystalline forms of pure silicon and germanium.	2. Examples: silicon "Si" and germanium "Ge" crystals with impurity atoms of As, Sb, P etc. or In B, Aℓ etc.
3 The number of free electrons in the conduction band and the no. of holes in valence band is exactly equal and very small indeed.	3. The number of free electrons and holes is never equal. There is excess of electrons in n-type semi-conductors and excess of holes in p-type semi-conductors.
4 Its electrical conductivity is low.	4. Its electrical conductivity is high.
5 Its electrical conductivity is a function of temperature alone.	5. Its electrical conductivity depends upon the temperature as well as on the quantity of impurity atoms doped the structure.

Intrinsic carrier concentration

Expression for electron density

Let dn_e is the electron density in the conduction band in the energy interval E and E + dE then,

$$dn_e = Z(E)F(E)dE \quad \text{------------- (1)}$$

Thus $n_e = \int_{Ec}^{\infty} Z(E)f(E)dE$

Where F(E) is the probability of electrons occupying the energy state E.

and $F(E) = \left[1 + \exp(E - E_F)/KT\right]^{-1}$

In conduction band $E - E_F \gg KT$

So $F(E) = e^{-(E - E_F)/KT} = e^{(E_F - E)/KT}$

Z (E) dE is the energy state density in the energy interval E and E + dE.

and is given by
$$Z(E)dE = \frac{4\pi}{h^3}(2m_e)^{\frac{3}{2}} E^{\frac{1}{2}} dE$$

Since electron moves in a perpendicular potential hence, m is replaced by m_e* = effective mass and since E_C bottom level of conduction band and E be any arbitrary level in the conduction band therefore E is replaced by E - E_C

So, $Z(E)dE = \frac{4\pi}{h^3}\left(2m_e{}^*\right)^{\frac{3}{2}}\left(E - E_C\right)^{\frac{1}{2}} dE$

Hence

$$dn_e = \frac{4\pi}{h^3}\left(2m_e{}^*\right)^{\frac{3}{2}}\left(E - E_C\right)^{\frac{1}{2}} e^{(E_F - E)/KT} dE$$

So $n_e = \int_{Ec}^{\infty} \frac{4\pi}{h^3}\left(2m_e{}^*\right)^{\frac{3}{2}}\left(E - E_C\right)^{\frac{1}{2}} e^{(E_F - E)/KT} dE$

$$= \frac{4\pi}{h^3}\left(2m_e{}^*\right)^{\frac{3}{2}} e^{E_F/KT} \int_{Ec}^{\infty}\left(E - E_C\right)^{\frac{1}{2}} e^{-E/KT} dE$$

Let $E - E_C = x \Rightarrow E = E_C + x$ and $dE = dx$

When $E \to E_C; x \to 0$

When $E \to \infty; x \to \infty$

Hence

$$n_e = \frac{4\pi}{h^3}\left(2m_e^*\right)^{\frac{3}{2}} e^{E_F/KT} \int_0^\infty x^{\frac{1}{2}} e^{-(E_C+x)/KT}\, dx$$

$$= \frac{4\pi}{h^3}\left(2m_e^*\right)^{\frac{3}{2}} e^{(E_F-E_C)/KT} \int_0^\infty x^{\frac{1}{2}} e^{\frac{-x}{KT}}\, dx$$

Using gamma function, we have $\displaystyle\int_0^\infty x^{\frac{1}{2}} e^{\frac{-x}{KT}}\, dx = (KT)^{\frac{3}{2}} \frac{\sqrt{\pi}}{2}$

So, $n_e = \dfrac{4\pi}{h^3}\left(2m_e^*\right)^{\frac{3}{2}} e^{(E_F-E_C)/KT} \times (KT)^{\frac{3}{2}} \dfrac{\sqrt{\pi}}{2}$

$$\therefore n_e = 2\left(\frac{2m_e^* \pi KT}{h^2}\right)^{\frac{3}{2}} e^{(E_F-E_C)/KT} = N_C e^{(E_F-E_C)/KT}$$

Where $N_C = 2\left(\dfrac{2m_e^* \pi KT}{h^2}\right)^{\frac{3}{2}}$

This is the expression for the electron density in conduction band.

Expression for hole density

If n_h be the hole density then in a similar procedure by substitution of $E = E_V - E$ in the expression of Z(E) and integrating from $-\infty$ to Ev we can derive

$$n_h = 2\left(\frac{2m_h^* \pi KT}{h^2}\right)^{\frac{3}{2}} e^{(E_V-E_F)/KT} = N_V e^{(E_V-E_F)/KT}$$

Where $N_V = 2\left(\dfrac{2m_h^* \pi KT}{h^2}\right)^{\frac{3}{2}}$

Where m_h^* is the effective mass of the hole.

Expression for Intrinsic Carrier concentration

In case of intrinsic semiconductor the electron concentration and hole concentration are same.

So, $n_e = n_p = n_i$ = intrinsic carrier concentration

Now $n_i^2 = n_e n_h = 2\left(\dfrac{2m_h^* \pi KT}{h^2}\right)^{\frac{3}{2}} e^{(E_V-E_F)/KT} \times 2\left(\dfrac{2m_e^* \pi KT}{h^2}\right)^{\frac{3}{2}} e^{(E_F-E_C)/KT}$

$$= 4\left(\frac{2\pi KT}{h^2}\right)^3 \left(m_e^* m_h^*\right)^{\frac{3}{2}} e^{(E_V - E_C)/KT}$$

$$= 4\left(\frac{2\pi KT}{h^2}\right)^3 \left(m_e^* m_h^*\right)^{\frac{3}{2}} e^{\frac{-E_g}{KT}} \quad \text{(Since } E_g = E_c - E_v\text{)}$$

Hence $\boxed{n_i = 2\left(\frac{2\pi KT}{h^2}\right)^{\frac{3}{2}} \left(m_e^* m_h^*\right)^{\frac{3}{4}} e^{\frac{-E_g}{2KT}}}$

or $\boxed{n_i = \left(N_C N_V\right)^{\frac{1}{2}} e^{\frac{-E_g}{2kT}}}$

Variation of Intrinsic carrier concentration with temperature

The equation of intrinsic carrier concentration can be re written as:

$$n_i = 2\left(\frac{2\pi KT}{h^2}\right)^{\frac{3}{2}} \left(m_e^* m_h^*\right)^{\frac{3}{4}} e^{\frac{-E_g}{2KT}} = 2\left(\frac{2\pi K}{h^2}\right)^{\frac{3}{2}} \left(m_e^* m_h^*\right)^{\frac{3}{4}} T^{\frac{3}{2}} e^{\frac{-E_g}{2KT}}$$

The above relation indicates that the carrier concentration varies with temperature. It may be approximated to

$$n_i = 10^{21.7} T^{\frac{3}{2}} \times 10^{\frac{-2500 E_g}{T}}$$

The following important points may be inferred from the above relation:

1) The intrinsic concentration is independent of the Fermi level
2) The intrinsic concentration depends exponentially on the band gap value.
3) The intrinsic concentration also strongly depends on the temperature
4) The factor 2 in the exponent indicates that two charge carriers are created when one covalent bond is broken.

Fermi Level

In case of intrinsic semiconductor the electron concentration and hole concentration are same.

i,e , $n_e = n_p$

So, $2\left(\frac{2m_e^* \pi KT}{h^2}\right)^{\frac{3}{2}} e^{(E_F - E_C)/KT} = 2\left(\frac{2m_h^* \pi KT}{h^2}\right)^{\frac{3}{2}} e^{(E_V - E_F)/KT}$

$$\Rightarrow \left(m_e^*\right)^{\frac{3}{2}} e^{\frac{E_F - E_C}{KT}} = \left(m_h^*\right)^{\frac{3}{2}} e^{\frac{E_V - E_F}{KT}}$$

$$\Rightarrow e^{\frac{2E_F}{KT}} = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{\frac{E_V + E_C}{KT}}$$

Taking logarithms on both sides, we have

$$\frac{2E_F}{KT} = \frac{3}{2}\ln\frac{m_h^*}{m_e^*} + \left(\frac{E_v + E_c}{KT}\right) \qquad \text{So,} \quad \boxed{E_F = \left(\frac{E_v + E_c}{2}\right) + \frac{3kT}{4}\ln\frac{m_h^*}{m_e^*}}$$

$$\text{Now} \quad \frac{E_v + E_c}{2} = \frac{E_c - E_v}{2} + E_v$$

$$\text{So,} \quad E_F = \frac{E_c - E_v}{2} + E_v + \frac{3KT}{4}\ln\frac{m_h^*}{m_e^*} = \frac{E_g}{2} + E_v + \frac{3KT}{4}\ln\frac{m_h^*}{m_e^*}$$

If we denote the top of the Valance band Ev as zero level then $E_V = 0$

So $\qquad \boxed{E_F = \frac{E_g}{2} + \frac{3kT}{4}\ln\frac{m_h^*}{m_e^*}}$

If we assume $m_e^* = m_h^*$ then $\boxed{E_F = \frac{E_v + E_c}{2}}$

If we denote the top of the Valance band Ev as zero level then $E_V = 0$

Then $\boxed{E_F = \frac{E_c}{2} = \frac{E_g}{2}}$

Fermi Level and its variation with Temperature in an Intrinsic semiconductor

Fermi level is located half way between the valence and conduction band if $m_e^* = m_h^*$.

If $m_e^* < m_h^*$ fermi level is just above the middle.

If $m_e^* > m_h^*$ fermi level is just below the middle.

With an increase in temperature the Fermi level gets displaced up word slightly towards the conduction band if $m_e^* < m_h^*$ and down word towards the valence band if $m_e^* > m_h^*$.

In most of the materials the shift of fermi level on account of $m_e^* \neq m_h^*$ is insignificant. Therefore the fermi level on an intrinsic semiconductor may be considered as independent of temperature and at middle of the band gap.
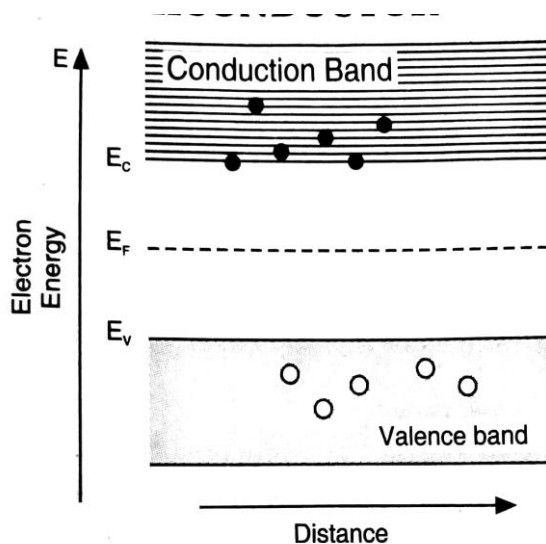
Fermi level in Intrinsic semiconductor
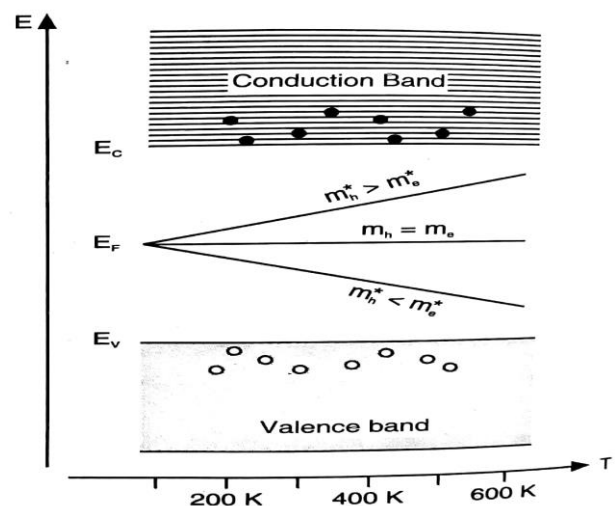
Variation of Fermi level with temperature

Electrical Conductivity of intrinsic semoconductor

Electrical conductivity $= \sigma = \sigma_e + \sigma_h = (n_e e \mu_e + n_h e \mu_h)$

Where μ_e and μ_h are the mobility of electron and hole respectively, e is the electronic charge

Since in case of intrinsic semiconductor $n_e = n_h == n_i$

So, $\boxed{\sigma = n_i e (\mu_e + \mu_h)}$

But $n_i = 2 \left(\dfrac{2\pi KT}{h^2} \right)^{\frac{3}{2}} \left(m_e^* m_h^* \right)^{\frac{3}{4}} e^{\frac{-E_g}{2KT}}$

So $\sigma = 2e \left(\mu_e + \mu_h \right) \left(\dfrac{2\pi KT}{h^2} \right)^{\frac{3}{2}} \left(m_e^* m_h^* \right)^{\frac{3}{4}} e^{\frac{-E_g}{2KT}}$

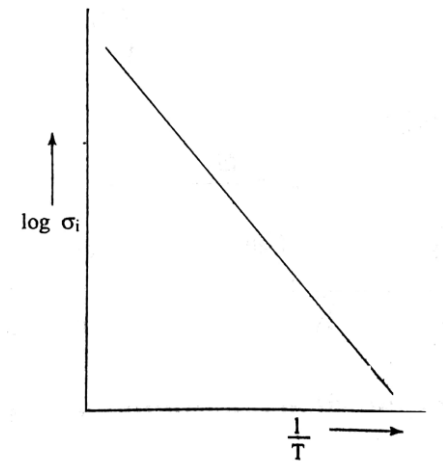$\Rightarrow \quad \sigma = A \, e^{\frac{-E_g}{2KT}}$ ------------------------(1)

$\Rightarrow$ Where A is a constant and $A = 2e \left(\mu_e + \mu_h \right) \left(\dfrac{2\pi KT}{h^2} \right)^{\frac{3}{2}} \left(m_e^* m_h^* \right)^{\frac{3}{4}}$

(in this case μ_e and μ_h both are proportional to

$T^{\frac{-3}{2}}$

Now taking logarithm of both the sides of equation (1)

We have, $\quad \ln \sigma = \ln A - E_g / 2KT$

If we draw a graph by taking 1/T along X-axis and $\ln\sigma$ along Y- axis then the nature of the graph will be like the figure which shows that conductivity increases with increase in temperature.

Carrier concentration in N type semiconductor:

Density of electrons in a conduction band is

$$n_e = 2 \left(\dfrac{2\pi m_e^* KT}{h^2} \right)^{\frac{3}{2}} e^{(E_F - E_C)/KT}$$

If N_d is the density of donor atom and E_d is the donor energy level. At the low temperature donor levels are filled with the electron. When temperature increases donor atoms are ionized and density in conduction band increases.

Now density of ionized donor atom is

$$N_d \{ 1 - F(E_d) \} = N_d \left(1 - \dfrac{1}{1 + e^{\frac{(E_d - E_F)}{KT}}} \right)$$

In this case we assume that the Fermi level lies just above the donor level such that $E_F - E_d \gg KT$

Hence $\left(1 + e^{\frac{(E_d - E_F)}{KT}}\right)^{-1} = 1 - e^{\frac{(E_d - E_F)}{KT}}$

So, $N_d\{1 - F(E_d)\} = N_d e^{\frac{(E_d - E_F)}{KT}}$

At low temperature concentration of electron in conduction band is equal to the concentration of ionized atoms in donor level

So, $n_e = N_d\{1 - F(E_d)\}$

$$\Rightarrow 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}} e^{(E_F - E_C)/KT} = N_d e^{\frac{(E_d - E_F)}{KT}}$$

$$\Rightarrow \exp\left(\frac{(E_F - E_C - E_d + E_F)}{KT}\right) = \frac{N_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}}$$

$$\Rightarrow \frac{2E_F}{KT} = \frac{E_C + E_d}{KT} + \log \frac{N_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}}$$

$$\Rightarrow E_F = \frac{E_C + E_d}{2} + \frac{KT}{2} \log \frac{N_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}}$$

$$\Rightarrow E_F = \frac{E_C + E_d}{2} + KT \log \frac{(N_d)^{\frac{1}{2}}}{\left[2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}\right]^{\frac{1}{2}}}$$

At 0° K, $\boxed{\dfrac{E_C + E_d}{2} = E_F}$

I.e. at 0° K Fermi level lies exactly at the middle of the donor level and the bottom of the conduction band.

So,

$$n_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}} e^{\dfrac{\frac{E_C+E_d}{2}+KT\log\dfrac{(N_d)^{\frac{1}{2}}}{\left[2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}\right]^{\frac{1}{2}}}-E_C}{KT}}$$

$$= 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}} \times \frac{(N_d)^{\frac{1}{2}}}{\left[2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}\right]^{\frac{1}{2}}} \times e^{\frac{E_d-E_C}{2KT}}$$

$$\therefore n_e = 2(N_d)^{\frac{1}{2}}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{4}} e^{\frac{E_d-E_C}{2KT}}$$

This is the expression for the density of electrons in conduction band at low temperature which is directly proportional to the square root of the donor concentration.

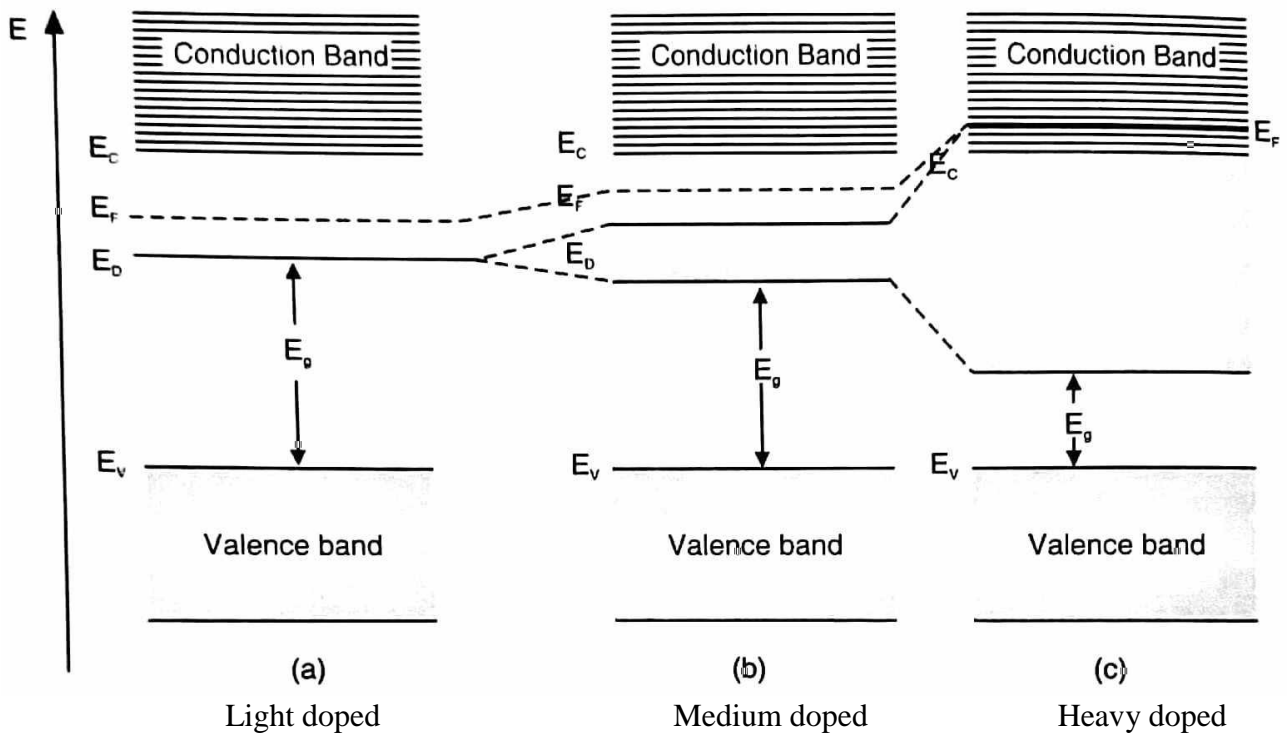**Variation of fermi level**
Variation with concentration
   (a) N-type semiconductor
When a small pentavalent impurity is added (low concentration) to a pure semiconductor then donor levels formed just below the conduction band and the fermi level lies in between donor level (E_D)and bottom of conduction band (E_C). In this case the donor level is discrete due to large separation between the atoms and no interaction at all.
When donor concentration is increased (medium doping) then separation between impurity atom reduces and overlapping of orbits takes place by which donor level form an energy band and the fermi level is pushed further towards conduction band and decreases forbidden energy gap..
When donor concentration is further increased (heavy doping) donor level broaden and decreases the energy gap further and the donor level overlap with the conduction band and fermi level further pushed towards conduction band and lies with in conduction band.
Thus with increase in concentration of donor impurity fermi level shift towards conduction band and finally moves to conduction band when the donor band overlaps on the conduction band.

|		
(a)	(b)	(c)
Light doped	Medium doped	Heavy doped

(b) P-type semiconductor

When a small trivalent impurity is added (low concentration) to a pure semiconductor then acceptor level formed just above the valance band and the fermi level (E_F)lies in between acceptor level (E_A)and top of valence band (E_V). In this case the acceptor level is discrete due to large separation between the atoms and no interaction at all.

When acceptor concentration is increased (medium doping) then separation between impurity atom reduces and overlapping of orbits takes place by which acceptor level form an energy band and the fermi level is pushed further towards valence band and decreases forbidden energy gap..

When acceptor concentration is further increased (heavy doping) acceptor level broaden and decreases the energy gap further and the acceptor level overlap with the valence band and fermi level further pushed towards valence band and lies with in valence band.

Thus with increase in concentration of acceptor impurity fermi level shift towards valence band and finally moves to valence band when the acceptor band overlaps on the conduction band.

(a)	(b)	(c)
Light doped	Medium doped	Heavy doped
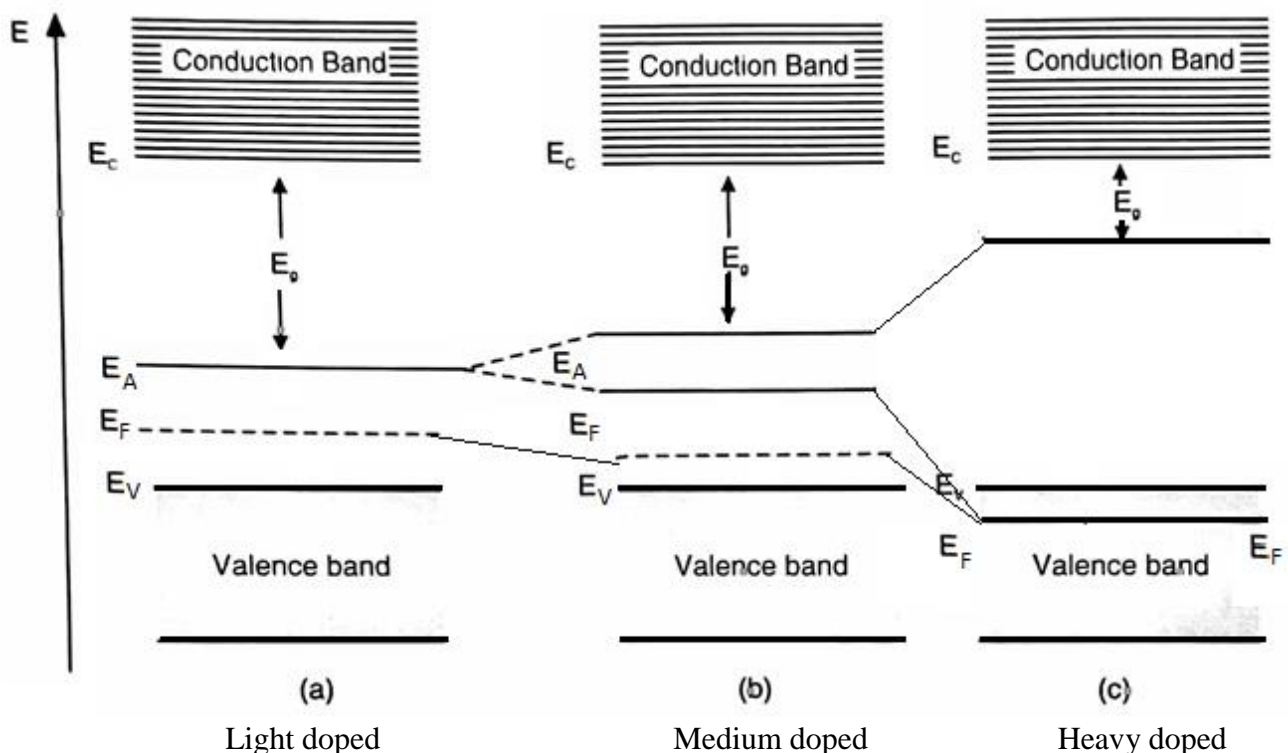
Variation with Temperature

(a) N-type semiconductor

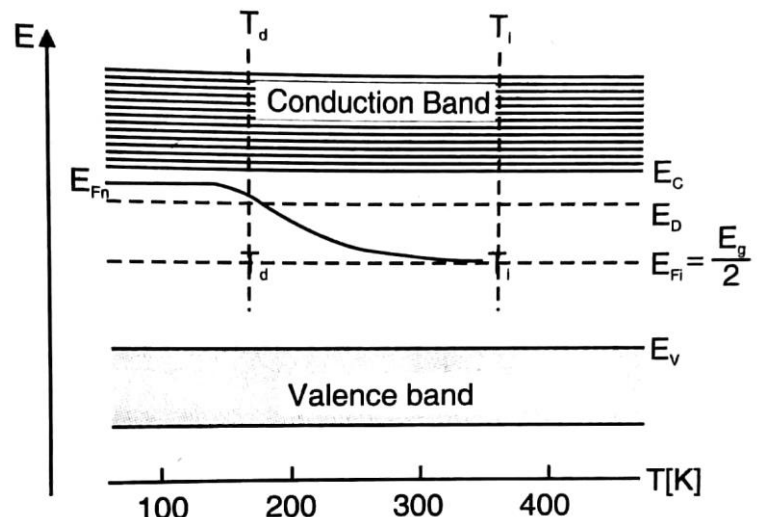At 0^0K the fermi level E_{Fn} lies between the donor level and the bottom of the conduction band.

i,e $E_{Fn} = \dfrac{E_C + E_D}{2}$ at T = 0K

When temperature increases the donor level depleted and the fermi level moves downwards. At the temperature of complete depletion of donor levels (Td) the fermi level coincides with the donor level (ED) Thus $E_{Fn} = E_D$ at T = Td

As the temperature goes further above Td Fermi level shifts down words linearly and at a temperature Ti the N-type semiconductor losses its extrinsic character and fermi level approaches the intrinsic value

Thus $E_{Fn} = E_{Fi} = \dfrac{E_g}{2}$ at $T \ge Ti$

(a) P-type semiconductor

At 0^0K the fermi level E_{Fn} lies between the acceptor level and the top of the valence band.

i,e $E_{FP} = \dfrac{E_V + E_A}{2}$ at T = 0K

When temperature increases the acceptor level is gradually filled and the fermi level moves upwards. At the temperature of saturation (Ts) the fermi level coincides with the acceptor level level (EA) Thus $E_{FP} = E_A$ at T = Ts

As the temperature goes further above Ts Fermi level shifts up words linearly and at a temperature Ti the N-type semiconductor losses its extrinsic character and fermi level approaches the intrinsic value

Thus $E_{FP} = E_{Fi} = \dfrac{E_g}{2}$ at $T \ge Ti$
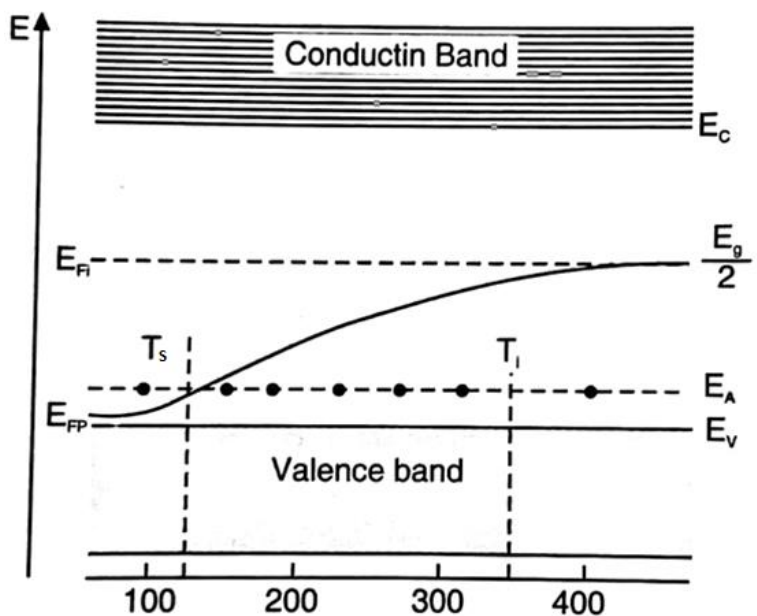
Hall Effect :- If a metal or a semiconductor carrying a current (I) is subjected to a transverse magnetic field B, a potential difference V_H is produced in a direction normal to both the magnetic field and current directions. This is called Hall effect.

Explanation

Any plane perpendicular to the current flow direction is an equipotential surface. Therefore, the potential difference between front and rear faces of such surfaces is zero. Now if a magnetic field is applied normal to such a surface and
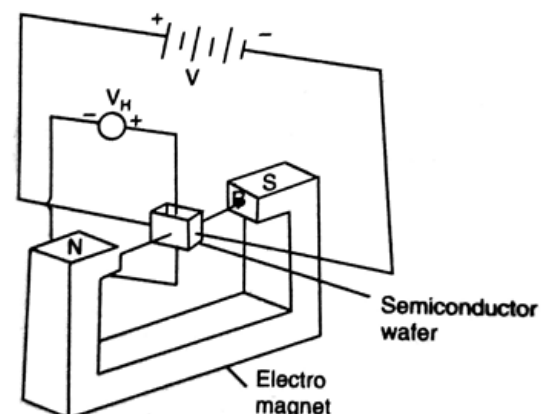
hence to the direction of current flow in it , then a transverse potential difference is produced between the two faces.

Derivation of Hall Co-efficient

Let us consider a P-type semiconductor slab ABCDEFGH. Let DH= length of the slab

AD = width 'w', (distance between the surface where Hall voltage is developed)
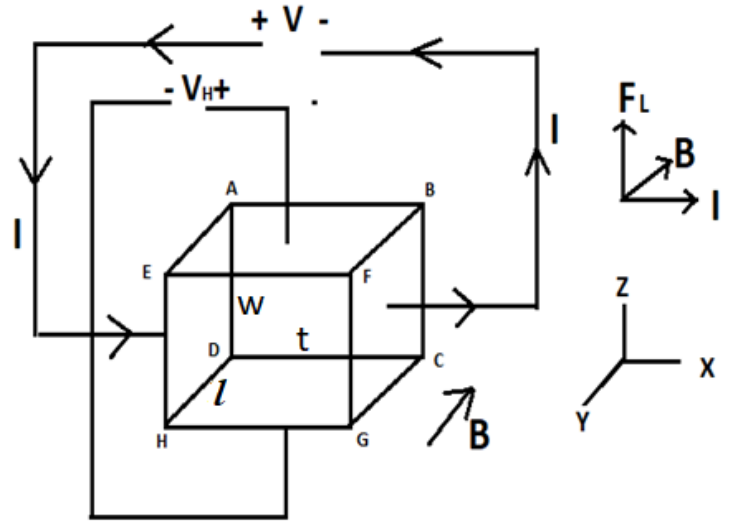
DC = thickness 't' (distance between the end along the direction of current)

Area of the side ABCD = A= wt

Let 'p' be the hole density

Let a current I passed through the slab along X-axis. (along the thickness)

Then I = $peAV_d$, Where V_d is the drift velocity and 'e' is the electrical charge associated with hole.

Then the current density $J = \dfrac{I}{A} = peV_d$ -------(1)

Let a transverse magnetic field **B** is applied along HD direction. Due to this magnetic field a Lorentz or magnetic force $F_L = eV_dB$ will be developed by which the holes will be drifted towards the surface ABFE. (by Flemings left hand rule magnetic force will act along Z-axis). Also equivalent negative charges will be drifted towards CDHG. These opposite charges produce an electric field call hall field E_H. Due to this Hall field an electric force ($F_E = eE_H$) will experience and under equilibrium position electric force is equal to Magnetic force. i,e $F_E = F_L$. => $eE_H = eV_dB$.

If V_H is the Hall voltage, then $E_H = \dfrac{V_H}{w}$ -------------(2)

So, $\dfrac{V_H}{w} = BV_d$ ----------(3)

From equation (1) $V_d = \dfrac{J}{pe}$, So $\dfrac{V_H}{w} = \dfrac{BJ}{pe} = \dfrac{BI}{peA} = \dfrac{BI}{pewt}$

So, $V_H = \dfrac{BI}{pet}$ ------------------(4)

This is the expression for Hall Voltage

Hall Coefficient

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

Thus $R_H = \dfrac{E_H}{JB} = \dfrac{V_H / w}{JB}$ ----------(5)

Using equation (4) $R_H = \dfrac{BI}{petwJB} = \dfrac{BJ}{peJB} = \dfrac{1}{pe}$

Thus $R_H = \dfrac{1}{pe}$ ----------(6)

This is expression for Hall coefficient

From equation (5)

$$R_H = \dfrac{V_H / w}{JB} = \dfrac{V_H / w}{IB / wt} = \dfrac{V_H t}{IB}$$

Thus $R_H = \dfrac{V_H t}{IB}$ This is another expression for Hall coefficient.

Hall coefficient is negative for n-type semiconductor (because e is negative) while the same is positive in the case of p-type semiconductor (because e is positive)

Unit of R_H is m^3/C or m^3/A-s.

Applications of Hall Effect:

Determination of Carrier Concentration

The expressions for the carrier concentrations of electrons (n) and holes (p) in terms of Hall coefficient are given by

$$n = \dfrac{-1}{R_H e} \quad \text{and} \quad p = \dfrac{1}{R_H e} \text{ respectively}$$

Determine the Mobility (Hall Mobility)

Mobility expression for the electrons (μ_n) and the holes (μ_p), expressed in terms of Hall coefficient is given by,

$$\mu_n = \sigma_n R_H \quad \text{and} \quad \mu_h = \sigma_h R_H \text{ respectively}$$

Where, σ_n and σ_p represent the conductivity due to the electrons and the holes, respectively.

Determination Magnetic Flux Density

Magnetic flux density can be determined by using the formula

$$B = \dfrac{V_H t}{R_H I}$$

Determination of drift velocity

Drift velocity can be determined by using the formula $V_d = \dfrac{V_H}{Bw}$