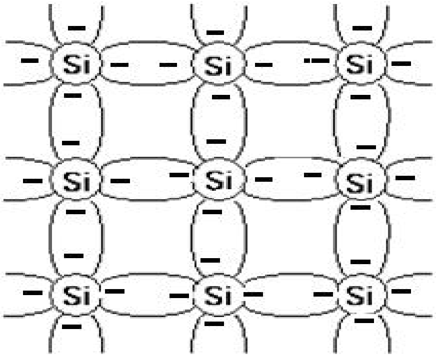
## SEMICONDUCTORS

Material which allows partial flow of electricity through it is called semiconductor .Conductivity of semiconductor lies between conductors and insulators.

Silicon and Germanium are the examples for semiconductors. The energy gap for Si is 1.1eV and for Ge is 0.7eV.

## INTRINSIC or PURE SEMICONDUCTOR



Let us consider 'Si' with atomic no. 14 and valence is 4. All the silicon atoms form covalent bonds with the neighboring Si atom and no electron is free for conduction at temperature 0 k. Hence pure silicon acts as *insulator* at absolute o k, as the temperature increases above 0 k, these covalent bonds break and some electrons are released. These electrons move in the crystal freely and responsible for conductivity. So they are called free electrons. Each electron leaves behind an empty space called a hole which also acts as current carrier. These electrons and holes move in opposite directions under the effect of external field and constitute current.

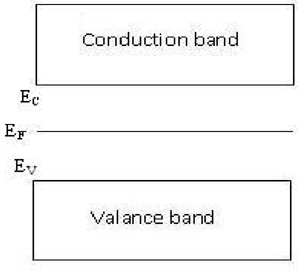
## ELECTRON CONCENTRATION IN THE CONDUCTION BAND OF INTRINSIC SEMICONDUCTOR

The no. of electrons per unit volume having energy in a range E and E+dE in the conduction band of an intrinsic semiconductor is,

dn = Z(E)dE F(E) ----------(1)

where F(E) represents the Fermi distribution function gives the probability of occupation of electron with energy E.

$$F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{K_B T}\right)}$$



Z(E) is the density of states i.e. no. of available states per unit volume of semiconductor.

$$Z(E) = \frac{4\Pi}{h^3}(2m)^{3/2}E^{1/2}$$

$$dn = \frac{4\Pi}{h^3}(2m)^{3/2}E^{1/2} \cdot \frac{1}{1+\exp\left(\frac{E-E_F}{K_B T}\right)} dE$$

For conduction band,

$$dn = \frac{4\Pi}{h^3}(2m^*_e)^{3/2}(E-Ec)^{1/2} \cdot \frac{1}{1+\exp\left(\frac{E-E_F}{K_BT}\right)} dE \text{ -------------- } (2)$$

Where $m_e^*$ is effective mass of electron in the conduction band.

in the above equation, for conduction band, $\exp\left(\frac{E-E_F}{K_BT}\right) >> 1$ so 1 can be neglected in the denominator of the equ.(2).

$$dn = \frac{4\Pi}{h^3}(2m^*_e)^{3/2}(E-Ec)^{1/2} \exp\left(\frac{-(E-E_F)}{K_BT}\right) \text{-------------} (3)$$

To get the total no. of electrons per unit vol. in the conduction band is we have to integrate the above equ. Between the bottom of the conduction to top of the conduction band.

$$\therefore n = \frac{4\Pi}{h^3}(2m^*_e)^{3/2} \int_{E_c}^{\infty} (E-Ec)^{1/2} \exp\left(\frac{-(E-E_F)}{K_BT}\right) dE$$

$$dn = \frac{4\Pi}{h^3}(2m^*_e)^{3/2} \int_{E_c}^{\infty} (E-Ec)^{1/2} \exp\left(\frac{-(E-E_F+E_c-E_c)}{K_BT}\right) dE$$

$$n = \frac{4\Pi}{h^3}(2m^*_e)^{3/2} \exp\left(\frac{(E_F-E_c)}{K_BT}\right) \int_{E_c}^{\infty} (E-Ec)^{1/2} \exp\left(\frac{-(E-E_c)}{K_BT}\right) dE$$

put $x = \left(\frac{(E-E_c)}{K_BT}\right)$, so that $dE = K_BTdx$

Lower Limit: when $E = E_c$, $x = 0$ and
Upper Limit: when $E = \infty$, $x = \infty$

$$\therefore n = \frac{4\Pi}{h^3}(2m^*_e)^{3/2} \exp\left(\frac{(E_F-E_c)}{K_BT}\right) \int_{0}^{\infty} e^{-x}(xK_BT)^{1/2} K_BT\, dx$$

$$n = \frac{4\Pi}{h^3}(2m^*_ek_BT)^{3/2} \exp\left(\frac{(E_F-E_c)}{K_BT}\right) \int_{0}^{\infty} e^{-x}(x)^{1/2}\, dx$$

$$n = 4\Pi \left[\frac{2m^*_e k_B T}{h^2}\right]^{3/2} \exp\left(\frac{(E_F-E_c)}{K_BT}\right) \frac{\sqrt{\pi}}{2}$$

$$n = 2\left[\frac{2\,\Pi m_e^* k_B T}{h^2}\right]^{3/2} \exp\left(-\frac{(E_c - E_F)}{K_B T}\right)$$

$$n = N_c \exp\left(-\frac{(E_c - E_F)}{K_B T}\right)$$

Where $N_c = 2\left[\frac{2\,\Pi m_e^* k_B T}{h^2}\right]^{3/2}$

**HOLE CONCENTRATION IN THE VALENCE BAND OF INTRINSIC SEMI CONDUCTOR**

The no. of holes per unit volume having energy in a range E and E+dE in the valence band of an intrinsic semiconductor is,

dp = Z(E)dE [1-F(E)] ----------(1)

where [1-F(E) ]represents the probability of absence of electron in the particular energy level with energy E.

$$[1-F(E)] = 1 - \frac{1}{1 + \exp\left(\frac{E - E_F}{K_B T}\right)} = \frac{\exp\left(\frac{E - E_F}{K_B T}\right)}{1 + \exp\left(\frac{E - E_F}{K_B T}\right)}$$

For the valance band 1>> $\exp\left(\frac{E - E_F}{K_B T}\right)$.

So exponential term can be neglected in the denominator of the above equation.

$$\therefore\ [1-F(E)] = \exp\left(\frac{E - E_F}{K_B T}\right)$$

$$dP = \frac{4\Pi}{h^3}(2m)^{3/2} E^{1/2} \exp\left(\frac{E - E_F}{K_B T}\right) dE$$

For valance band,

$$dp = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} (E_v - E)^{1/2} \exp\left(\frac{E - E_F}{K_B T}\right) dE$$

To get the total no. of holes in the V.B. we have to integrate the above equation between the limits bottom of the V.B. to top of the V.B.

$$p = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} \exp\left(\frac{E - E_F}{K_B T}\right) dE$$

$$p = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} \int_{-\infty}^{E_v} (E_v-E)^{1/2} \exp\left(\frac{E-E_F+E_V-E_V}{K_BT}\right) dE$$

$$p = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} \exp\left(\frac{E_V-E_F}{K_BT}\right) \int_{-\infty}^{E_v} (E_v-E)^{1/2} \exp-\left(\frac{E_V-E}{K_BT}\right) dE$$

put $\left(\frac{E_V-E}{K_BT}\right) = x$ ; $dE = -dx\, K_BT$

Lower Limit: when $E = -\infty$, $x = \infty$.
Upper Limit: when $E = E_v$ , $x = 0$.

$$\therefore p = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} \exp\left(\frac{E_V-E_F}{K_BT}\right) \int_{\infty}^{0} e^{-x} (xK_BT)^{1/2} (-K_BT\, dx)$$

$$p = \frac{4\Pi}{h^3}( m_h^* K_BT)^{3/2} \exp\left(\frac{E_V-E_F}{K_BT}\right) \int_{0}^{\infty} e^{-x} x^{1/2}\, dx$$

$$p = \frac{4\Pi}{h^3}(2 m_h^* K_BT)^{3/2} \exp\left(\frac{E_V-E_F}{K_BT}\right) \frac{\sqrt{\Pi}}{2}$$

$$p = 2\left(\frac{2m_h^*\pi k_BT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V-E_F}{K_BT}\right) \text{ or}$$

$$p = N_v \exp-\left(\frac{E_F-E_V}{K_BT}\right) \text{----------- (2)}$$

Where $N_v = 2\left(\frac{2m_h^*\pi k_BT}{h^2}\right)^{\frac{3}{2}}$

Equ. (2) gives the no. of holes in the V.B of the intrinsic semi conductor.

**LOCATION OF FERMI LEVEL IN INTRINSIC SEMICONDUCTOR**

In intrinsic semiconductor no. of electrons in the C.B and no. of holes in the V.B are equal.

$\therefore$ n = p

$$N_c \exp\left(-\frac{(E_c-E_F)}{K_BT}\right) = N_v \exp-\left(\frac{E_F-E_V}{K_BT}\right)$$

$$\exp\left(\frac{-E_c+E_F+E_F-E_v}{K_BT}\right)=\frac{\mathrm{Nv}}{\mathrm{N_C}}$$

$$\frac{2E_F}{K_BT}-\frac{(E_C+E_V)}{K_BT}=\ln\frac{\mathrm{Nv}}{\mathrm{N_C}}$$

$$E_F=\frac{(\mathrm{Ec}+\mathrm{Ev})}{2}+\frac{K_BT}{2}\ln\frac{\mathrm{Nv}}{\mathrm{N_C}}\text{ ----------- (1)}$$

At T = 0 k,

$$E_F=\frac{(\mathrm{Ec}+\mathrm{Ev})}{2}\text{ -------- (2)}$$

Fermi energy level lies exactly in the middle of the forbidden gap at absolute zero K.

**INTRINSIC CARRIER CONCENTRATION ($n_i$)** [law of mass action]

In the intrinsic semiconductor, n = p = $n_i$. Where $n_i$ is known as intrinsic carrier concentration.

$\therefore$ np = $n_i^2$

$$n_i^2=2\left[\frac{2\,\mathrm{m_e^*}\pi\mathrm{k_B T}}{\mathrm{h^2}}\right]^{3/2}\exp\left(-\frac{(E_c-E_F)}{K_BT}\right)2\left(\frac{2m_h^*\pi k_BT}{h^2}\right)\exp-\left(\frac{E_F-E_V}{K_BT}\right)$$

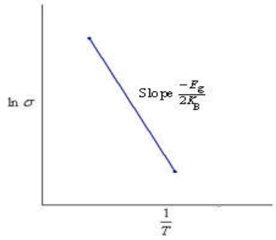
$$n_i^2=4\left[\frac{2\,\Pi\mathrm{k_B T}}{\mathrm{h^2}}\right]^3\left(m_e^*m_h^*\right)^{3/2}\exp\left(\frac{-E_c+E_F-E_F+E_V)}{K_BT}\right)$$

$$n_i^2=4\left[\frac{2\,\Pi\mathrm{k_B T}}{\mathrm{h^2}}\right]^3\left(m_e^*m_h^*\right)^{3/2}\exp\left(\frac{-(E_c-E_V)}{K_BT}\right)$$

$$n_i=2\left[\frac{2\,\Pi\mathrm{k_B T}}{\mathrm{h^2}}\right]^{3/2}\left(m_e^*m_h^*\right)^{3/4}\exp\left(\frac{-E_g)}{2K_BT}\right)\quad\text{(since } E_c\text{-}E_v=E_g\text{)}$$

This equ Shows that for a given semiconductor the product of holes and electron concentration at a given temp. is equal to square of the intrinsic semiconductor carrier concentration. This is called law of mass action and holds both for intrinsic and extrinsic semiconductors.

**CONDUCTIVITY OF INTRINSIC SEMICONDUCTORS**



When the electric field is applied to the semiconductor, charge carriers acquire velocity.

$v_d$ α E

$v_d = \mu E$ --------- (1)

where μ is called mobility of charge carriers.

Current density $J = ne\, v_d$

$J = ne\mu E$ ---------- (2)
This is in the form of $J = \sigma E$
Where $\sigma = ne\mu$ --------- (3) is conductivity
For electrons $\sigma_n = ne\mu_e$
For holes $\sigma_p = pe\mu_h$

Where $\mu_e$ ,$\mu_h$ are mobilities of electrons and holes respectively.

$\therefore\ \sigma = ne\mu_e + pe\mu_h$

$= (n\mu_e + p\mu_h)e$

$= n_i(\mu_e + \mu_h)e$ --------- (4) where $n_i$ is called intrinsic carrier concentration.

$$\sigma = 2\left[\frac{2\Pi k_B T}{h^2}\right]^{3/2} \left(m_e^* m_h^*\right)^{3/4} \exp\left(\frac{-E_g)}{2K_B T}\right) (\mu_e + \mu_h)e$$

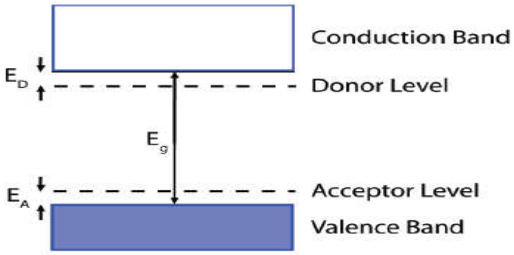
$$\sigma = \sigma_o \exp\left(\frac{-E_g)}{2K_B T}\right) \quad \text{where } \sigma_o = 2\left[\frac{2\Pi k_B T}{h^2}\right]^{3/2} \left(m_e^* m_h^*\right)^{3/4} (\mu_e + \mu_h)e$$

$$\ln\sigma = \ln \sigma_o - \frac{E_g}{2K_B T} \text{ -----------(4)}$$

The above equ. gives the expression for conductivity of intrinsic semiconductor.

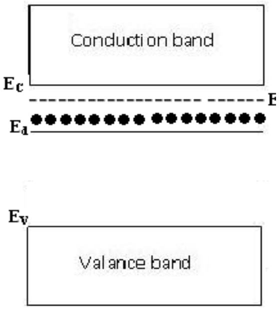
**EXTRINSIC SEMICONDUCTORS**

To increase the conductivity of pure semiconductors some impurities are added. This process is called doping**.** When impurities are added to semiconductor the available energy levels are altered. One or more energy levels are appeared in the band structure. Doping may create energy levels within the forbidden band.

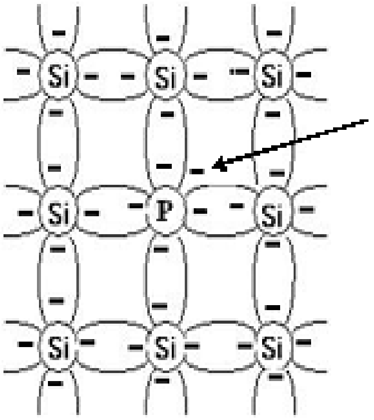


**N-TYPE SEMICONDUCTOR**

When pentavalent impurities such as phosphorous, Arsenic or Antimony is introduced into Si, or Ge, four of its valence electrons form 4 covalent bonds with other 4 neighboring Si or Ge atoms while the fifth valence electron loosely bound to its nucleus. A small amount of energy is required to detach fifth electron from its nucleus and make it free to conduct. So pentavalent impurities are known as donor impurities. The energy level corresponding to the fifth valence electron lies in the band gap just below the C.B. edge as shown in figure.



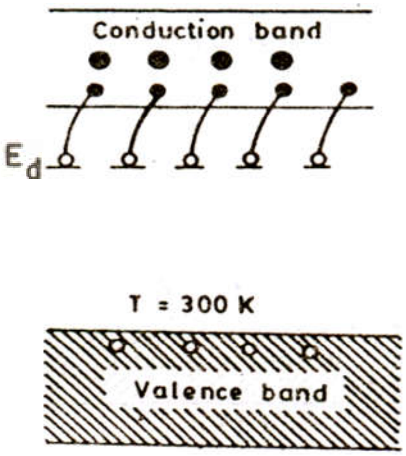
## ELECTRON CONCENTRATION IN N-TYPE SEMICONDUCTOR



The energy level diagram for n-type semiconductor is shown in fig. At 0k all donor levels are unionized state that is all donor levels are occupied with electrons. As temperature increases slightly some of the donors ionized and contribute electrons to the conduction band. Also some of the valence electrons may jump to the conduction band leaving hole in valence band. The no. of holes produced quite small in this process. Therefore Fermi level must lie near the middle of the donor level and bottom of the conduction band. Let there be $N_d$ donors per unit volume occupying donor levels with energy $E_d$. The electron concentration in the conduction band is given by

$$n = N_c \exp\left(-\frac{(E_c - E_F)}{K_B T}\right) \text{----------} (1)$$

The electron concentration must be equal to the sum of concentration of ionized donors in donor levels and concentration of thermally generated holes in valence band. i.e.



$$n = N_d^+ + p \text{ ----------------} (2)$$

If donors concentration is high, the holes generated can be neglected.

$$\therefore\ n \approx N_d^+ \text{ ---------------} (3)$$

The concentration of ionized donors can be written as

$$N_d^+ = N_d[1 - F(E_d)]$$

$$= N_d\left[1 - \frac{1}{1 + \exp\left(\frac{E_d - E_F}{K_B T}\right)}\right]$$

$$= N_d\left[\frac{\exp\left(\frac{E_d - E_F}{K_B T}\right)}{1 + \exp\left(\frac{E_d - E_F}{K_B T}\right)}\right]$$

$$= N_d \exp\left[-\left(\frac{E_F - E_d}{K_B T}\right)\right] \text{---------} (4)$$

In n-type semiconductor $E_F$ lies above the $E_d$, $1 >> \exp\left(\frac{E_d - E_F}{K_B T}\right)$. So exponential term can be neglected in the denominator of the above equation.

From equations (3) and (4), we get

$$N_c \exp\left[-\left(\frac{E_c - E_F}{K_B T}\right)\right] = N_d \exp\left[-\left(\frac{E_F - E_d}{K_B T}\right)\right]$$

$$\exp\left(\frac{-E_c + E_F + E_F - E_d}{K_B T}\right) = \frac{N_d}{N_c}$$

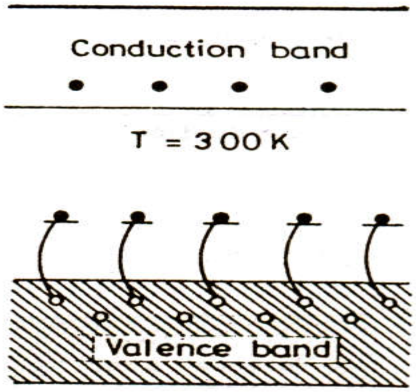
$$\left(\frac{2E_F}{K_B T} - \frac{(E_c + E_d)}{K_B T}\right) = \ln\frac{N_d}{N_c}$$

$$E_F = \frac{E_c + E_d}{2} + \frac{K_B T}{2} \ln\frac{N_d}{N_c} \text{ --------- (5)}$$

Substitute the value of $E_F$ in equ.(1)

$$n = N_c \exp\left(\frac{-E_c}{K_B T} + \frac{E_c + E_d}{2K_B T} + \frac{\ln\frac{N_d}{N_c}}{2}\right)$$

$$n = N_c \exp\left(\frac{-2E_c + E_c + E_d}{2K_B T} + \frac{\ln\frac{N_d}{N_c}}{2}\right)$$



$$n = N_c \exp\left(\frac{E_d - E_c}{2K_B T} + \ln\left(\frac{N_d}{N_c}\right)^{1/2}\right)$$

$$n = N_c \left(\frac{N_d}{N_c}\right)^{1/2} \exp\left(\frac{E_d - E_c}{2K_B T}\right)$$

$$n = \left(N_c N_d\right)^{1/2} \exp\left(\frac{E_d - E_c}{2K_B T}\right) \text{ or ----------- (6)}$$

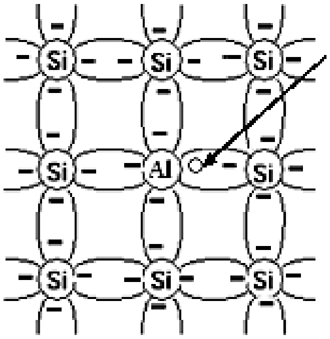
$$n = \left(N_c N_d\right)^{1/2} \exp\left(\frac{-\Delta E}{2K_B T}\right) \text{ --------------- (7)}$$

Where $-\Delta E = E_d - E_c$ represents the ionization energy of donors.

## P-TYPE SEMICONDUCTOR

When trivalent impurity such as aluminum, boron, gallium or indium is added to pure silicon, it forms 3 covalent bonds with the neighboring 3 silicon atoms while the fourth bond is not completed due to the deficiency of one electron. Thus the trivalent impurity atom has a tendency to accept one electron from neighboring silicon atom to complete the fourth covalent bond. The energy level corresponding to the electron deficiency that is 'hole' is located above the valence bond and is called acceptor level.

In this type of semiconductor majority charge carriers are holes and minority charge carriers are electrons, called p-type semiconductor.



## CONDUCTIVITY OF EXTRINSIC SEMICONDUCTORS

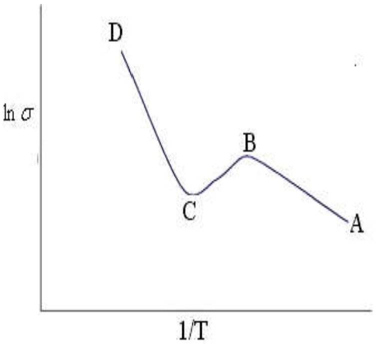
The expression for conductivity for n-type semiconductors is
$\sigma_e = ne\mu_e$ ---------- (1) and

For p-type material is $\sigma_p = ne\mu_h$ --------- (2)

Where $\mu_e$ and $\mu_h$ are mobilities of electrons and holes.

Under the condition of thermal equilibrium electron and holes are uniformly distributed in semiconductor and the average velocity of charge carriers is zero, no current flows.

Conductivity is temperature dependent as shown in figure.



At low temp the conductivity increases with increase of temperature. This is due to increase in the no. of conduction electrons due to ionization of donor impurities. Conductivity reaches maximum value B in the graph all donors is ionized. Conductivity decreases further increase with temperature. This is due to decrease of mobility because of scattering of electrons from the periodic potential field. A sharp rise in conductivity from C to D is due to large increase in intrinsic conductivity.

## DRIFT & DIFFUSION

The net current that flows across semi conducting crystal has two components.
(i) Drift current
(ii) Diffusion current

## DRIFT CURRENT

**When voltage is applied electrons attracted towards the positive potentials and holes attracted towards the negative potential. This net movement of charge carriers is called drift.**
Due to the application of voltage charge carriers attain drift velocity $V_d$ , which is proportional to the electric field E.

$V_d \alpha E$

$V_d = \mu E$ -------- (1)

Where $\mu$ is mobility of charge carriers. The drift current density $J_e$ due to electrons is defined as the charge flowing across unit area per unit time due to their drift under the influence of field is given by
$J_{e(drift)} = ne\, V_d$ or

$J_{e(drift)} = ne\mu_e E$ ------- (2)

Where $\mu_e$ is mobility of electrons. The drift current density due to holes in the valence band is

$J_{h(druft)} = pe\mu_h E$ -------- (3)

So the total drift current is

$$J_{(drift)} = J_{e(drift)} + J_{h(drift)}$$
$$= e\,(n\mu_e + p\mu_h)\,E \text{ ----------- } (4)$$

The above equation is applicable to intrinsic as well as extrinsic semiconductors. Drift current depends upon two variables

(i) carrier concentration
(ii) electric field

**DIFFUSION CURRENT**

In addition to the drift motion, the chare carriers in semiconductor move by diffusion of charge carriers from high concentration to low concentration region. Current produced by the diffusion of the charge carriers is called diffusion current.

Suppose when light or temperature is incident on the semiconductor, additional electron and hole pairs generated and they diffuse throughout the semiconductor to restore the equilibrium condition.

Let $\Delta n$, $\Delta p$ be the excess charge of electron and holes respectively. According to Fick's law, diffusion current is proportional to rate of flow of excess charge.

$\therefore$ rate of flow of excess charge $\propto -\dfrac{\partial}{\partial x}(\Delta n)$ or

Rate of flow of excess charge = $-D_e \dfrac{\partial}{\partial x}(\Delta n)$

$\therefore$ $J_{e(diff.)}$ = (-e) rate of flow of excess electrons

$$= eD_e \frac{\partial}{\partial x}(\Delta n) \text{ ---------- } (1)$$

Similarly diffusion current density due to holes is

$J_{h(diff.)}$ = (e) rate of change of excess holes

$$= -D_h \frac{\partial}{\partial x}(\Delta p) \text{ ------------ } (2)$$

$\therefore$ Total current density in semiconductor due to electrons is $J_e = J_{e(drift)} + J_{e(diff.)}$

$$= ne\mu_e E + eD_e \frac{\partial}{\partial x}(\Delta n)$$

$$= (n\mu_e E + D_e \frac{\partial}{\partial x}(\Delta n))\, e \text{ ---------- } (3)$$

Current density due to holes is

$J_h = J_{h(drift)} + J_{h(diff.)}$

$$= pe\mu_h E + (-D_h \frac{\partial}{\partial x}(\Delta p))$$

$$J_h = (p\mu_h E - D_h \frac{\partial}{\partial x}(\Delta p))\, e \text{ ---------- } (4)$$

**EINSTEIN'S RELATION**

Einstein's relation gives the direct relation between diffusion coefficient and mobility of charge carriers. At equilibrium condition drift current balances and opposite to the diffusion current .

$$\therefore\ ne\mu_e E = -\, eD_e \frac{\partial n}{\partial x} \text{ ---------- } (1)$$

$$ne\mu_e E = -(1/\mu_{e)}\ eD_e \frac{\partial n}{\partial x} \text{ ---------- } (2)$$

Einstein compared the movement of charge carriers with the gas molecules in a container.
According to Boltzmann's statistics the concentrations of gas molecules can be written as

$$n = C.\exp\left(\frac{-Fx}{K_B T}\right)$$ where x is distance and F = eE is force acting on the charge carriers

$$\frac{\partial n}{\partial x} = C.\exp\left(\frac{-eEx}{K_B T}\right).\ \left(\frac{-eE}{K_B T}\right) \quad , \quad \frac{\partial n}{\partial x} = n.\left(\frac{-eE}{K_B T}\right) \text{ ----------- } (3)$$

$$F = neE = K_B T\, \frac{\partial n}{\partial x} \text{ ----------- } (4)$$

$$\therefore\ ne\mu_e E = neD_e\left(\frac{eE}{K_B T}\right)$$

$$\frac{D_e}{\mu_e} = \frac{K_B T}{e} \text{ ---------- (2) for electrons} \qquad \frac{D_h}{\mu_h} = \frac{K_B T}{e} \text{ --------- (3) for holes}$$

## HALL EFFECT

When a semiconductor carrying current ‘i’ is placed in a magnetic field which is perpendicular to the direction of current, an electric field is developed across the material in a direction perpendicular to both the current direction and magnetic field direction. This phenomenon is known as Hall Effect.

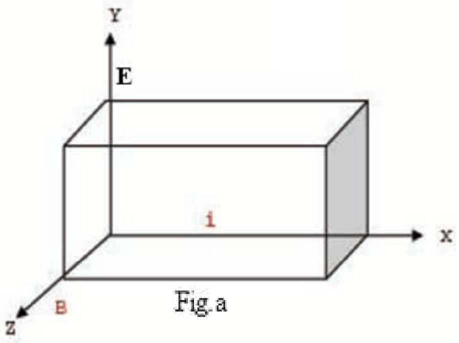


Fig.a

### Explanation

Consider a piece of semiconductor in which current passing along x-axis. When a magnetic field B is applied along z-direction an electric field is appeared along y-direction.

If the sample is p-type semiconductor holes move with velocity v in x-direction. As they move across the semiconductor these holes experience a transverse force due to magnetic field. This force drives the holes on the lower surface as shown in figure. As a result the lower surface becomes positively charged and upper surface becomes negatively charged and creating Hall field along y-direction.

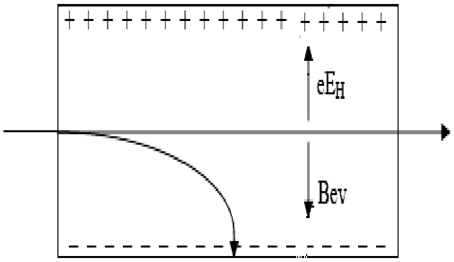


Fig.b N-Type Semiconductor

If the sample is an n-type semiconductor majority charge carriers are electrons, these electrons experience a force ‘Bev’ in downward direction and lower face gets negatively charged and upper face gets positively charged which is shown in fig.b

Consider a rectangular slab of n-type semiconductor carrying current in positive x-direction under the magnetic field electrons are deflected to the lower surface because of force ‘Bev’ due to magnetic field and upper surface gets positively charged because of this electric field a force ‘$eE_H$’ acts on electrons in upward direction. The two opposing forces ‘Bev’ and ‘$eE_H$’ establish equilibrium. So

$$Bev = eE_H$$

$$Bv = E_H \text{ ---------- } (1)$$

Let ‘J’ be the current density then

$$J = nev \quad \text{or} \quad v = \frac{J}{ne} \text{ --------- } (2)$$

From (1) and (2), $\frac{BJ}{ne} = E_H$ -------- (3)

Hall Effect depends on the current density J and magnetic field B.

$$E_H \propto JB$$

$E_H = R_H JB$ ----------- (4) Where $R_H$ is Hall coefficient.

From (3) and (4), $R_H = -\frac{1}{ne}$ ----------- (5)

-ve sign is used because the electric field developed in –ve y-direction.

For p-type semiconductors,

$$R_H = \frac{1}{pe} \text{ ---------- (6) where p is hole density.}$$

**DETERMINATION OF HALL COEFFICIENT ($R_H$)**

If $V_H$ be the Hall voltage across the sample of thickness‘t’

$$E_H = \frac{V_H}{t} \text{ --------- (7)}$$

From (4) and (7),

$$R_H JB = \frac{V_H}{t} \quad \text{or} \quad V_H = R_H JB \times t \text{ ------------ (8)}$$

If ‘b’ be the width of the sample then current density $J = \frac{I}{A}$

$$V_H = \frac{R_H IxBxt}{bxt} \quad \text{or}$$

$$R_H = \frac{V_H bxt}{IxB} \text{ ---------- (9)}$$

**SIGNIFICANCE OF HALL EFFECT**

1. By means of Hall Effect we can assess the type of semiconductor whether it is n-type or p-type. Hall coefficient is negative for n-type material.

2. Charge carrier concentration can be evaluated by means of Hall Effect.

$$R_H = \frac{1}{ne} \text{ or } n = \frac{1}{eR_H}$$

3. Mobility of charge carriers can be calculated by means of Hall Effect.

$$\sigma = ne\mu \text{ and } R_H = \frac{1}{ne}$$

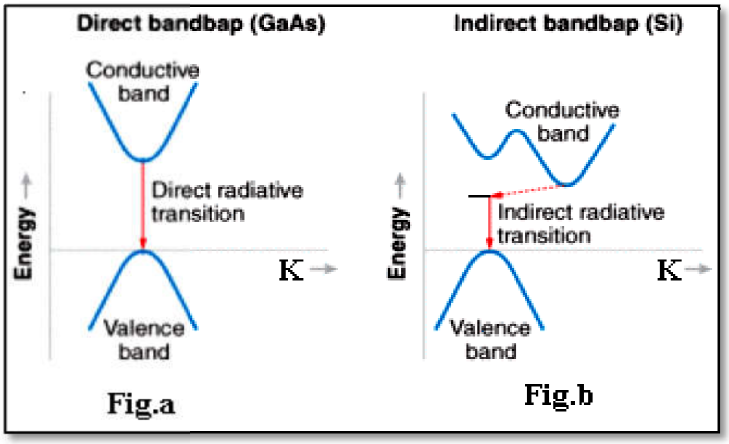
$$\therefore \mu = R_H \sigma$$

4. Hall Effect can be used to determine the power flow in electromagnetic wave

**DIRECT AND INDIRECT BANDGAP SEMICONDUCTORS**

According to the band theory of solids, the energy spectrum of electrons consists of large number of allowed energy bands and separated by forbidden regions. The lowest point of the C.B is called conduction band edge and the highest point in V.B is called valence band valence band edge. The gap between them is called band bap or forbidden gap. Based on the band gap semiconductors are classified into two types.

(i) Direct band gap semiconductors and
(ii) Indirect band gap semiconductors



**DIRECT BAND GAP SEMICONDUCTORS**

- Fig.a shows E-K curve for direct band gap semiconductor. In this case the maximum of the valence band and the minimum of the conduction band occurs at the same value of the 'K'.
- In direct band gap semiconductors electrons in the C.B directly recombine with the holes in the V.B.
- Energy is released in the form of photons. So LED's and Lasers diodes are prepared with them.
- In direct band gap semiconductors life time of charge carries is very less. (i.e excited electrons cannot stay long time in the higher energy states)
- Direct band gap semiconductors are formed by compound semiconductors. Ex. InP, GaAs etc.

**INDIRECT BAND GAP SEMICONDUCTORS**

- Fig b shows E-K curve for direct band gap semiconductor. In this case the maximum of the valence band and the minimum of the conduction band cannot occur at the same value of the 'K'.
- In indirect band gap semiconductors electrons in the C.B do not directly recombine with the holes in the V.B. Electrons are trapped in the energy gap called trapping centers.
- Energy is released in the form of heat.
- In indirect bandgap semiconductors life time of charge carries is longer. So they are used to amplify the signals in diodes and transistors.
- Indirect band gap semiconductors are formed by elemental semiconductors. Ex.Si, Ge.

## SHORT ANSWER QUESTIONS

1. Define semiconductor
2. State and explain Bloch's theorem
3. Differences between direct and indirect band gap semi conductors
4. Differences between Intrinsic and Extrinsic semi conductors
5. Write few applications of semiconductor
6. Write few applications of Hall Effect.
7. Define drift and diffusion currents
8. Explain electrical conductivity and resistivity in Intrinsic semiconductors with variation of temperature.
9. Explain electrical conductivity and resistivity in P Type semiconductors with variation of temperature
10. Explain electrical conductivity and resistivity in N Type semiconductors with variation of temperature
11. Derive the expression for Fermi level in Intrinsic semiconductors and explain its variation with temperature.
12. Derive the expression for Fermi level in P Type semiconductors and explain its variation with temperature.
13. Derive the expression for Fermi level in N type semiconductors and explain its variation with temperature.
14. Derive the expression for electric conductivity in Intrinsic semiconductors.
15. Indicate an energy level diagrams the conduction and valence bands, donor and acceptor levels for intrinsic semiconductor.

## LONG ANSWER QUESTIONS

16. Explain the classification of crystalline solids based on band theory

    Or

    Explain origin of energy bands in solids and based on energy bands. Distinguish conductor, semiconductor and insulator.
17. Derive the expression for carrier concentration in intrinsic semi conductors
18. Derive the expression for intrinsic carrier concentration and Fermi energy in intrinsic semi conductors
19. Derive the expression for electron concentration in n-type Extrinsic semiconductors.
20. Derive the expression for hole concentration in p-type Extrinsic semiconductors
21. Show that Fermi level is nearer to conduction band in a N-type semiconductor and discuss the variation of conductivity with temperature of an n-type semiconductor.
22. Explain the concept of drift and diffusion currents and hence derive the relation between diffusion and mobility

    Or

    Explain the concept of drift and diffusion currents and hence derive the Einstein's equation.
23. Explain Hall Effect in semiconductors and derive the expression for Hall coefficient. Write the applications of Hall effect

    Or

    State and explain Hall Effect in detail?

## NUMERICALS

1. The $R_H$ of a specimen is $3.66\times10^{-4}$ $m^{-3}c^{-1}$.Its resistivity is $8.93\times10^{-3}$ Ωm. Find μ and n.
2. The following data are given for intrinsic germanium at 300k $n_i = 2.4\times10^{19}/m^3$, $\mu_e$=0.39 $m^2 V^{-1} s^{-1}$, $\mu_p$=0.19 $m^2 V^{-1} s^{-1}$.Calculate the resistivity of sample.
3. The hall coefficient of a specimen is $3.66\times10^{-4}$ $m^3C^{-1}$. Its resistivity is $8.93\times10^{-3}$ $\Omega^{-m}$. Find carrier density and mobility of charge carriers.
4. Find the Diffusion coefficient of an electron in silicon at 300 K, if $\mu_e$ is 0.19 $m^2$/V-s
5. The resistivity of an intrinsic semiconductor is 4.5 ohm-m at 20°C and 2 ohm-m at 32ºC What is the energy gap.

# MULTIPLE CHOICE QUESTIONS

1. Solids with high value of conductivity are called:
   a. **Conductors** b. Non – metal c. Insulator d. Semi conductor

2. Flow of electrons is affected by the following
   a. Thermal vibrations b. Impurity atoms c. Crystal defects **d. All**

3. The unit of electrical conductivity is
   a**. ohm / metre** b. ohm / sq. M c. ohm / metre d. ohm / sq. m

4. All good conductors have high
   a. resistance b. electrical conductivity
   c. electrical and thermal conductivity d. **conductance**

5. The probability that an electron in a metal occupies the Fermi-level, at any temperature (>0 K) is:
   a. 0 b. 1 **c. 0.5** d. None of these

6. For metals conduction band and valenceband are
   a. Fully occupied b. Empty c. Partially occupied d. **Overlapping**

7. What is the correct statement for an insulator?
   a. The band gap energy is very high b. **The conduction band and valence cannot overlap**
   c. The conduction band and valence band may overlap
   d. The conduction band and valence cannot have very little difference of energy

8. P-type and N-type extrinsic semiconductors are formed by adding impurities of valency?
   a. 5 and 3 respectively. b. 5 and 4 respectively.
   c. **3 and 5 respectively.** d. 3 and 4 respectively

9. The bond that exists in a semiconductor is
   a. Ionic bond b. **Covalent bond** c. Metallic bond d. Hydrogen bond

10. A semiconductor is formed by ……… bonds.
    a. **Covalent** b. Electrovalent c. Co-ordinate d. None of the above

11. A semiconductor has ………… temperature coefficient of resistance.
    a. Positive b. Zero c. **Negative** d. None of the above

12. The most commonly used semiconductor is ………..
    a. Germanium b. **Silicon** c. Carbon d. Sulphur

13. 91. A semiconductor has generally……………… valence electrons.
    a. 2 b. 3 c. 6 d. **4**

14. The resistivity of pure germanium under standard conditions is about ………
    a. 6 x 104 Ω cm b. **60 Ω cm** c. 3 x 106 Ω cm d. 6 x 10-4 Ω cm

15. The resistivity of a pure silicon is about ……………
    a. 100 Ω cm b. 6000 Ω cm c. 3 x 105 Ω m d. 6 x 10-8 Ω cm

16. When a pure semiconductor is heated, its resistance …………..
    a. Goes up b. **Goes down** c. Remains the same d. Can't say

17. The strength of a semiconductor crystal comes from ……..
    a. Forces between nuclei b. Forces between protons
    c. **Electron-pair bonds** d. None of the above

18. When a pentavalent impurity is added to a pure semiconductor, it becomes ………
    a. An insulator b. An intrinsic semiconductor
    c. p-type semiconductor d. **n-type**

19. Addition of pentavalent impurity to a semiconductor creates many ……..
    a. **Free electrons** b. Holes c. Valence electrons d. Bound electrons

20. A pentavalent impurity has ………. Valence electrons
    a. 3 **b. 5** c. 4 d. 6

21. An n-type semiconductor is ………
    a. Positively charged b. Negatively charged c. **Electrically neutral** d. None of the above

22. A trivalent impurity has ….. valence electrons
    a. 4 b. 5 c. 6 **d. 3**

23. Addition of trivalent impurity to a semiconductor creates many ……..
    a. **Holes** b. Free electrons c. Valence electrons d. Bound electrons

24. A hole in a semiconductor is defined as ……………
    a. A free electron b. The incomplete part of an electron pair bond
    c. A free proton d. A free neutron

25. The impurity level in an extrinsic semiconductor is about ….. of pure semiconductor.
    a. 10 atoms for 108 atoms b. 1 atom for 108 atoms
    c. 1 atom for 104 atoms d. 1 atom for 100 atoms

26. As the doping to a pure semiconductor increases, the bulk resistance of the semiconductor ..
    a. Remains the same b. Increases c. Decreases d. None of the above

27. A hole and electron in close proximity would tend to ……….
    a. Repel each other b. **Attract each other**
    c. Have no effect on each other d. None of the above

28. In a semiconductor, current conduction is due to ……..
    a. Only holes b. Only free electrons
    c. **Holes and free electrons** d. None of the above

29. The random motion of holes and free electrons due to thermal agitation is called ……….
    a. **Diffusion** b. Pressure c. Ionisation d. None of the above

30. In an intrinsic semiconductor, the number of free electrons ………
    a. **Equals the number of holes** b. Is greater than the number of holes
    c. Is less than the number of holes d. None of the above

31. At room temperature, an intrinsic semiconductor has ……….
    a. Many holes only b. **A few free electrons and holes**
    c. Many free electrons only d. No holes or free electrons

32. At absolute temperature, an intrinsic semiconductor has ……….
    a. A few free electrons b. Many holes
    c. Many free electrons d.**No holes or free electrons**

33. Pure semiconductors which conduct electricity on heating are called ________ semiconductors
    a. n-type b. Extrinsic c**. Intrinsic** d. p-type

34. Number of free electrons in conduction band is equal to number of holes in valence band in _______ semiconductor
    a. n-type b. Extrinsic c**. Intrinsic** d. p-type

35. The intensity of light emitted by an LED depends on __________
    a. forward bias b. reverse bias c. band gap d. **forward current**

36. Photo diode always operate in _____ mode
    a. unbiased b. forward biased c**. reverse biased** d. none of the above

37. The process of adding controlled impurities to a semiconductor is known as:
    a. contamination b. Alloying c. Compounding d. **doping**

38. Which one of the following is not a charge carrier:
    a. electrons b. Ions c. Holes d. **gamma rays**

39. The photo current in a photo-diode depends on ______ of the incident light
    a. frequency b. Wavelength c**. Intensity** d. duration

40. Hall effect is true for
    a. Metals only b. Semiconductors only
    c**. Both metals and semiconductors** d. For N-type semiconductors only

41. In Hall effect, if only the direction of the magnetic field applied to the material is changed
    a. The value of Hall voltage appears b. The value of Hall voltage developed decreases
    c. **The value of Hall voltage developed in opposite direction, but its value remains constant**
    d. The Hall effect do not appear

42. What does conductivity of metals depend upon?
    a. The nature of the material b. **Number of free electrons**

c. Resistance of the metal d. Number of electrons

43. If the thickness of the material is reduced, the Hall voltage developed
    a. **Decreases** b. Increases
    c. Remains constant d. Changes the direction

44. If the magnitude of current is increased, the Hall voltage developed
    a. Decreases **b. Increases**
    c. Remains constant d. Changes the direction

45. What is the level that acts as a reference which separated the vacant and filled states at 0K?
    a. Excited level b. Ground level c. Valance orbit d. **Fermi Energy level**