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PH8252 - PHYSICS FOR INFORMATION SCIENCE

UNIT - II

SEMICONDUCTOR PHYSICS

Part B

1. (a) Obtain an expression for intrinsic carrier concentration in an intrinsic semiconductor

(OR)

(b)Derive an expression for the carrier concentration in an intrinsic semiconductor

(OR)

(c) Derive an expression for density of electrons in the conduction band and density of holes in the valence band of an intrinsic semiconductor.

(OR)

(d) Assuming the Fermi – Dirac distribution derive an expression for the concentration of electrons per unit volume in the conduction band of an intrinsic semiconductor.

(OR)

(e) Obtain an expression for intrinsic carrier concentration in an intrinsic semiconductor.

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In intrinsic semiconductors, both electrons and holes are charge carriers. The number of charge carriers per unit volume of the material is called carrier concentration. (Number of electrons in the conduction band (n) and number of holes in the valence band (p) per unit volume of the material).

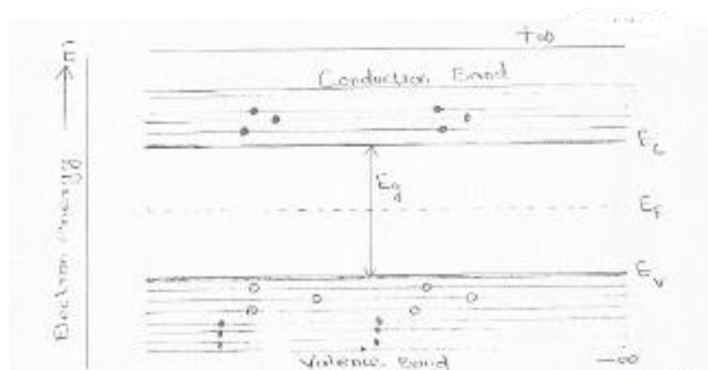
Calculation of density of electrons:

Let dn be the number of electrons available between energy level E and E + dE in the conduction band. Then dn can be written as

$$dn = Z(E)\, F(E)\, dE \text{ ------ } (1)$$

Where → Z (E) dE is the density of states in the energy interval E and E + dE and

F (E) is the probability of electron occupation.



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If E_c is the energy corresponding to the bottom of the conduction band, then the number of electrons in the conduction band

$$n = \int_{E_c}^{\infty} Z(E)F(E)dE \text{ ------ (2)}$$

The density of energy states is given by $Z(E)dE = \frac{4\pi}{h^3}(2m)^{3/2} E^{1/2} dE$ -------- (3)

The mass of the electron (m) is replaced by its effective mass m^*_e as the electrons move in periodic potential.

The bottom edge of the conduction band E_c corresponds to the potential energy of an electron at rest. Therefore $(E - E_c)$ will be the kinetic energy of the conduction electron at higher energy levels.

Therefore equation (3) becomes

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

The probability of an electron occupying an energy state E is given by

$$F(E) = \frac{1}{1 + e^{(E - E_F)/KT}}$$

$$F(E) = (1 + e^{(E - EF)/KT})^{-1} \text{ ------ (5)}$$

For all possible temperatures, $E - E_F \gg KT$

Hence 1 can be neglected.

$$\therefore F(E) = (e^{(E - E_F)/KT})^{-1}$$

$$F(E) = e^{(E_F - E)/KT} \text{ ------ (6)}$$

Substituting eqn (4) and eqn (6) in eqn (2 we get,

$$n = \int_{E_c}^{\infty} \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E - E_c)^{1/2} e^{(E_F - E)/KT} dE.$$

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

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{(E_F)/KT} \int_{E_c}^{\infty}(E - E_c)^{1/2} e^{(-E)/KT} dE \text{ ---- (7)}$$

To solve the above integral,

Let	When $E = E_c$	When $E = \infty$
$E - E_c = x$	$E = Ec + x$	$\infty - E_c = x$
$E = Ec + x$	$x = 0$	$x = \infty$
$dE = dx$		

Substituting the above values in eqn (7)

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

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

Using gamma function

$$\int_0^{\infty} x^{1/2}\ e^{(-x)/KT}\ dx = \ (KT)^{3/2}\ \frac{\pi^{1/2}}{2}$$

Hence, $n = \frac{4\pi}{h^3}\ (2m_e^*)^{3/2}\ e^{(E_F-\ E_C)/KT}\ (KT)^{3/2}\ \frac{\pi^{1/2}}{2}$

$$= \frac{4}{2h^3}\ (2\ m_e^* \pi KT)^{3/2}\ e^{(E_F-E_c)/KT}$$

$$n = 2(\frac{2m_e^*\pi KT}{h^2})^{3/2}\ e^{(E_F-E_C)/KT} \text{ ---------- (8)}$$

This is the expression for the number of electrons per unit volume of the material (or) band of an intrinsic semiconductor.

Calculation of density of holes in valence band:

Let d_p be the number of holes or vacancies available between energy level E and E+dE in valence band. Then d_p can be written as

$$d_p = Z\ (E)\ [1 - F(E\ )]dE \text{ ------ (9)}$$

Where Z (E) dE is the density of states in the energy interval E and E+dE and

$[1 - F(E\ )]$ is the probability of existence of a hole.

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If E_v is the energy corresponding to the top of the valence band, then the number of holes in the valence band.

$$P = \int_{-\infty}^{E_v} Z(E\ )[1 - F(E\ )]\ dE \text{ ------ (10)}$$

We know that, the density of energy states is given by

$$Z(E)dE = \frac{4\pi}{h^3}(2m)^{3/2}\ E^{1/2}dE \text{ ------ (11)}$$

The mass 'm' is replaced by the effective mass m^*_h

The top level of the valence band E_v corresponds to the potential energy of a hole at rest. Therefore $(E_v - E)$ will be the kinetic energy of the mobile hole at levels below E_v.

Therefore equation (11) becomes

$$Z\ (E)\ dE = \frac{4\pi}{h^3}\ (2m_h^*)^{3/2}\ (E_v - E)^{1/2} dE \text{ ------ (12)}$$

The probability of existence of a hole is given by

$$1 - F\ (E) = 1 - \frac{1}{1+\ e^{(E-\ E_F)/KT}}$$

$$= 1 - (1 +\ e^{(E-\ E_F)/KT})^{-1}$$

$$= 1 - (1 - e^{(E - E_F)/KT})$$

$= 1 - 1 + e^{(E - E_F)/KT}$

$1 - F(E) = e^{(E - E_F)/KT}$ ------- (13)

Substituting eqn (12) and eqn (13) in eqn (10) we get

$$P = \int_{-\infty}^{E_v} \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_v - E)^{1/2} e^{(E - E_F)/KT} dE$$

$$= \frac{4\pi}{h^3} (2m^*_h)^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{(E - E_F)/KT} dE$$

$$= \frac{4\pi}{h^3} (2m^*_h)^{3/2} e^{(-E_F)/KT} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{E/KT} dE \text{ ------ (14)}$$

To solve the above integral

Let $E_v - E = x$	When $E = -\infty$	When $E = E_v$
$E = E_v - x$	$-\infty = E_v - x$	$E_v = E_v - x$
$dE = -dx$	$x = E_v + \infty$	$x = E_v - E_v$
	$x = \infty$	$x = 0$

Substituting the above values in eqn (14)

We get,

$$P = \frac{4\pi}{h^3} (2m^*_h)^{3/2} e^{(-E_F)/KT} \int_{\infty}^{0} x^{1/2} e^{(E_v - x)/KT} (-dx)$$

$$P = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(E_v - E_F)/KT} \int_0^{\infty} x^{1/2} e^{(-x)/KT} (dx)$$

Using Gamma function,

$$\int_0^{\infty} x^{1/2} e^{(-x)/KT} dx = \frac{(KT)^{3/2}\pi^{1/2}}{2}$$

$$P = \frac{4\pi}{h^3} (2m^*_h)^{3/2} e^{(E_v - E_F)/KT} (KT)^{3/2} \frac{\pi^{1/2}}{2}$$

$$P = \frac{4}{h^3} (2m^*_h\pi KT)^{3/2} e^{(E_v - E_F)/KT}$$

$$P = 2 \left(\frac{2m^* h\pi KT}{h^2}\right)^{3/2} e^{(E_V - E_F)/KT} \text{ ------- (15)}$$

This is the expression for the number of holes per unit volume of the material (or) the concentration of holes in the valence band of an intrinsic semiconductor.

Carrier concentration:

In the case of intrinsic semiconductors, at thermal equilibrium, the number of electrons is equal to the number of holes.

Hence, $n = p = n_i$ is called intrinsic carrier concentration.

Therefore, $n_i^2 = n \, x \, p$

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$$n_i^2 = 2\left(\frac{2\pi\, m^*e\, KT}{h^2}\right)^{\frac{3}{2}} e^{(E_F - E_C)/KT}$$

$$= 2\left(\frac{2\pi\, m^* hKT}{h^2}\right)^{3/2} e^{(E_v - E_F)/KT}$$

$$= 4\left(\frac{2\pi KT}{h^2}\right)^{3/2} (m^*_e\, m^*_h)^{3/2}\, e^{(E_F - E_c + E_v - E_F)/KT}$$

$$= 4\left(\frac{2\pi KT}{h^2}\right)^{3/2} (m^*_e\, m^*_h)^{3/2}\, e^{(E_v - E_c)/KT}$$

Here, $E_c - E_v = Eg$

$$n_i^2 = 4\left(\frac{2\pi KT}{h^2}\right)^3 (m^*_e\, m^*_h)^{3/2}\, e^{(-E_g)/KT}$$

Hence

$$N_i = 2\left(\frac{2\pi KT}{h^2}\right)^{3/2} (m^*_e\, m^*_h)^{3/4}\, e^{(-E_g)/2KT} \text{ ------- } (16)$$

This is the expression for the carrier concentration of intrinsic semiconductor.

2. (a) Obtain an expression for the density of electrons in the conduction band of an N-type semiconductor.

(OR)

(b) Derive an expression for carrier concentration in N-type semiconductor.

(OR)

(c) Obtain an expression for the density of electrons in the conductor's band of an n-Type semiconductors and show that it is proportional to the square root of the donor concentration at low temperature. Also state what happens at high temperature.

(OR)

(d) Derive the relation for carrier concentration in N-type semiconductor.

(OR)

(e) Derive the expressions for carrier concentration in an 'n' type semiconductor. And deduce an expression for Fermi energy at 0K.

Carrier concentration in N-type semiconductors:

The energy level diagram is shown in figure.

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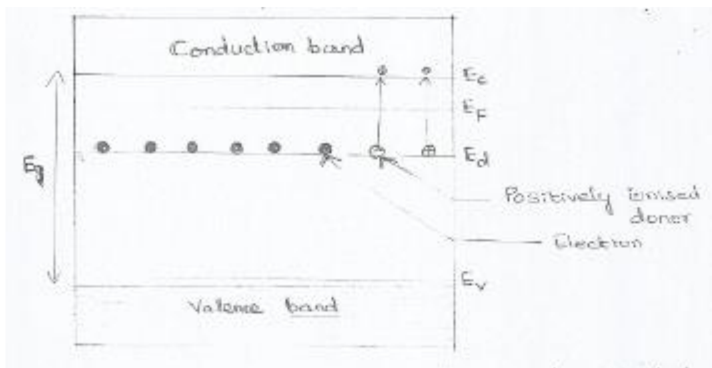

The donor level is just below the conduction band. Let N_d represents the donor concentrations and E_d represents the donor energy level.

Density of electrons per unit volume in the conduction band is given by

$$n = 2\left(\frac{2m^* e\pi KT}{h^2}\right)^{3/2} e^{(E_F - E_c)/KT} \text{ -------- } (1)$$

Where E_F is the energy of the Fermi level and E_c is the energy corresponding to bottom of the conduction band.

Density of ionized donors is given by

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

$$1 - F(E_d) = 1 - \frac{1}{1 + e^{(E_d - E_f)/kt}}$$

$$= 1 - \left[1 + e^{(E_d - E_F)/KT}\right]^{-1}$$

$$= 1 - \left[1 - e^{(E_d - E_F)/KT}\right]$$

$$= 1 - 1 + e^{(E_d - E_F)/KT}$$

$$= e^{(E_d - E_F)/KT}$$

$$\therefore N^+_d = N_d\, e^{(E_d - E_F)/KT}$$

At very low temperature, when electron – hole pairs are not generated due to breaking of covalent bonds the number of electrons in the conductors band must be equal to the number of ionized donors.

$$\text{i.e., } n = N_d^+$$

$$2\left(\frac{2m^* e\pi KT}{h^2}\right)^{3/2} e^{(E_F - E_c)/KT} = N_d\, e^{(E_d - E_F)/KT}$$

Taking logarithm on both sides we get

$$\log 2\left(\frac{2m^* e\pi KT}{h^2}\right)^{3/2} + \left(\frac{E_F - E_c}{KT}\right) = \log N_d + \left(\frac{E_d - E_F}{KT}\right)$$

$$\left(\frac{E_F - E_c}{KT}\right) - \left(\frac{E_d - E_F}{KT}\right) = \log N_d - \log 2\left(\frac{2\pi\, m^*}{h^2} eKT\right)^{3/2}$$

$$\frac{E_F - E_c - E_d + E_F}{KT} = \log \frac{N_d}{2(\frac{2\pi m^* eKT}{h^2})^{3/2}}$$

$$2E_F - (E_d + E_c) = KT\log \frac{N_d}{2\left(\frac{2\pi m^* eKT}{h^2}\right)^{\frac{3}{2}}}$$

$$2E_F = (E_d + E_c) + KT\log \frac{N_d}{2(\frac{2\pi m^* eKT}{h^2})^{3/2}}$$

$$E_F = \left(\frac{E_d + E_c}{2}\right) + \frac{KT}{2} \log \frac{N_d}{2(\frac{2\pi m^* KT}{h^2})^{\frac{3}{2}}} \text{ ------- (2)}$$

This is the equation Of Fermi level in N-type semiconductor.

The carrier concentration in the conduction band for N-type semiconductor is obtained by substituting the value of E_F from equation (2) in equation (1)

First simplify the exponential term,

$$\left(\frac{E_F - E_c}{KT}\right) = \frac{E_F}{KT} - \frac{E_c}{KT}$$

$$= \frac{\frac{E_d + E_c}{2} + \frac{KT}{2} \log \frac{N_d}{2(\frac{2\pi KT m_e^*}{h^2})^{3/2}}}{KT} - \frac{E_c}{KT}$$

$$= \frac{E_d + E_c}{2KT} - \frac{E_c}{KT} + \frac{1}{2} \log \frac{N_d}{2(\frac{2\pi m_e^* KT}{h^2})^{3/2}}$$

$$= \frac{E_d - E_c}{2KT} + \log \frac{(N_d)^{1/2}}{\left\{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}\right\}^{1/2}}$$

Therefore, $e^{(E_F - E_c)/KT} = e^{\left(\frac{E_d - E_c}{2KT} + \log \frac{N_d^{1/2}}{\left\{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}\right\}^{1/2}}\right)}$

$$= e^{\left(\frac{E_d - E_c}{2KT}\right)} \; x \; \frac{N_d^{1/2}}{\left\{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}\right\}^{1/2}}$$

[Since $e^{x+y} = e^x . e^y$ *and* $e^{\log x} = x$

Substituting this in eqn (1) we get

$$n = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} e^{\left(\frac{E_d - E_c}{2KT}\right)} \; x \; \frac{N_d^{1/2}}{\left\{2\left(\frac{2\pi KT m_e^*}{h^2}\right)^{3/2}\right\}}$$

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

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This is the expression for the carrier concentration in N-type semiconductors.

Variation of Fermi level with temperature and impurity concentration:

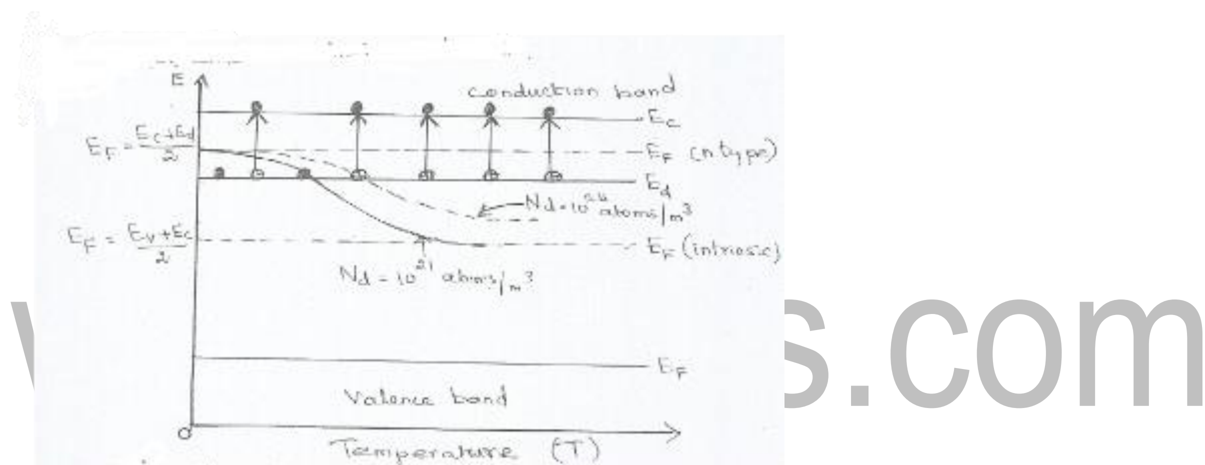
Expression for Fermi level in N-type semiconductor is given by

$$E_F = \left(\frac{E_d + E_c}{2}\right) + \frac{KT}{2}\log\frac{N_d}{2\left(\frac{2\pi m^* eKT}{h^2}\right)^{3/2}}$$

At T = 0K, the above expression reduces to

$$E_F = \frac{E_{d+}E_c}{2}$$

So the Fermi level lies exactly half way between donor level and conduction band



* As the temperature increases, more and more donor atoms are ionized and Fermi level E_F shifts downwards.

* For a particular temperature, all the donor atoms are fully ionized where Fermi level crosses the donor level.

* Further increase in temperature results in generation of electron – hole pairs due to breaking of covalent bonds and the material tends to behave in an intrinsic manner.

* Therefore, Fermi level gradually moves towards intrinsic Fermi level E_f (intrinsic)

Variation of Fermi level with donor concentration:

* Lowering of Fermi level from $E_F = E_d + E_c$ to intrinsic Fermi level with rise of temperature is to intrinsic Fermi level with rise of temperature is slow in the case of higher donor concentration material than the lower concentration material.

* This is because highly doped semiconductor will behave in intrinsic manner only after all the donor atoms are ionized.

3. (a) Derive an expression for carrier concentration in p-type semiconductor and explain the Variation of carrier concentration with temperature.

(OR)

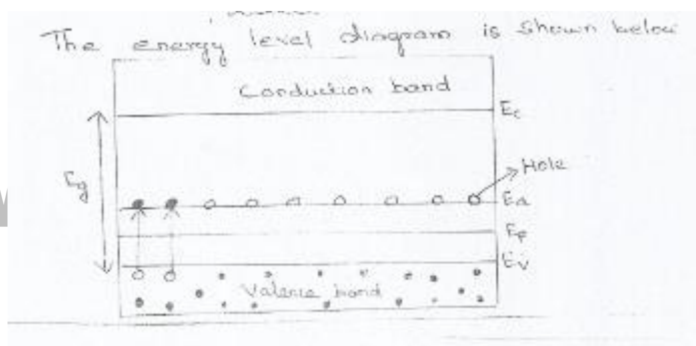
(b) Derive an expression for carrier concentration in p-type semiconductor.

(OR)

(c) Obtain an expression for the density of holes in a p-type semiconductor and show that It is proportional to the square root of the acceptor concentration at low temperatures.

(OR)

(d) Derive an expression for the density of holes in the valence band of p-type Semiconductor.



Let N_a represents the acceptor concentration and E_a represents the acceptor energy level.

Density of holes per unit volume in the valence band is given by

$$P = 2\left(\frac{2m^* h\,\pi KT}{h^2}\right)^{3/2} e^{(E_v - E_F)/KT} \text{ ------- (1)}$$

The concentration of the ionized acceptors is given by

$$N^-_a = N_a F(E_a)$$

$$F(E_a) = \frac{1}{1 + e^{(E_a - E_F)/KT}}$$

$$F(E_a) = \left(1 + e^{(E_a - E_F)/KT}\right)^{-1}$$

Since $(E_a - E_F) \gg KT$. Hence 1 can be neglected.

$$\therefore\ F(E_a) = \left(e^{(E_a - E_F)/KT}\right)^{-1}$$

$F(E_a) = e^{(E_f - E_a)/KT}$

Equation (2) becomes

$N_a^- = N_a e^{(E_F - E_a)/KT}$

At very low temperatures the density of the holes in the valence band is equal to the density of ionized acceptors.

i.e., $p = N_a^-$

$$2\left(\frac{2m^* h\pi KT}{h^2}\right)^{3/2} e^{(E_v - E_F)/KT} = N_a e^{(E_F - E_a)/KT}$$

Taking logarithm on both sides we get

$$\log 2\left(\frac{2\pi m^* hKT}{h^2}\right)^{3/2} + \left(\frac{E_v - E_F}{KT}\right) = \log N_a + \left(\frac{E_F - E_a}{KT}\right)$$

$$\left(\frac{E_v - E_F}{KT}\right) - \left(\frac{E_F - E_a}{KT}\right) = \log N_a - \log 2\left(\frac{2\pi m^* h\,KT}{h^2}\right)^{3/2}$$

$$\frac{E_v - E_F - E_F + E_a}{KT} = \log \frac{N_a}{2\left(\frac{2\pi m^* h\,KT}{h^2}\right)^{3/2}}$$

$$E_v + E_a - 2E_F = KT \log \frac{N_a}{2\left(\frac{2\pi\, m^* h\,KT}{h^2}\right)^{3/2}}$$

$$-2E_F = -(E_v + E_a) + KT \log \frac{N_a}{2\left(\frac{2\pi m^* h\,KT}{h^2}\right)^{3/2}}$$

$$\therefore E_F = \left(\frac{E_v + E_a}{2}\right) - \frac{KT}{2} \log \frac{N_a}{2\left(\frac{2\pi m^* h\,KT}{h^2}\right)^{3/2}} \quad \text{------- (2)}$$

This is the equation of Fermi level in p – type semiconductor.

The carrier concentration in the valence band for p-type semiconductor is obtained by substituting the value of E_F from equation (2) in equation (1)

First simplify the exponential term

$$\left(\frac{E_v - E_F}{KT}\right) = \frac{E_v}{KT} - \frac{E_F}{KT}$$

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

$$= \frac{E_v}{KT} - \frac{(E_v + E_a)}{2KT} + \frac{1}{2} \log \frac{N_a}{2\left(\frac{2\pi KT m_h^*}{h^2}\right)^{3/2}}$$

$$= \frac{(E_v - E_a)}{2KT} + \log \frac{(N_a)^{1/2}}{\left\{2\left(\frac{2\pi KT m_h^*}{h^2}\right)^{3/2}\right\}^{1/2}}$$

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$$\therefore \quad e^{(E_v - E_F)/KT} = e^{\left[\frac{(E_v - E_a)}{2KT} + \log \frac{(N_a)^{1/2}}{\left\{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}\right\}^{1/2}}\right]}$$

$$= e^{\frac{(E_v - E_a)}{2KT}} \; x \; \frac{(N_a)^{1/2}}{\left\{2\left(\frac{2\pi KT m_h^*}{h^2}\right)^{3/2}\right\}^{1/2}}$$

$$[Since\ e^{x+y} = e^x . e^y \ and\ e^{\log x} = x]$$

Substituting this in eqn(1) we get

$$p = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} \; e^{\frac{(E_v - E_a)}{2KT}} \; x \; \frac{(N_a)^{1/2}}{\left\{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}\right\}^{1/2}}$$

$$p = (2N_a)^{1/2} \left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/4} e^{\frac{(E_v - E_a)}{2KT}}$$

This is the expression for the carrier concentration in p-type semiconductors.

Variation of Fermi level with temperature and impurity concentration:

Expression for Fermi level in p – type semiconductors is given by

$$E_F = \left(\frac{E_v + E_a}{2}\right) - \frac{KT}{2} \log \frac{N_a}{2\left(\frac{2\pi m^* h KT}{h^2}\right)^{3/2}}$$

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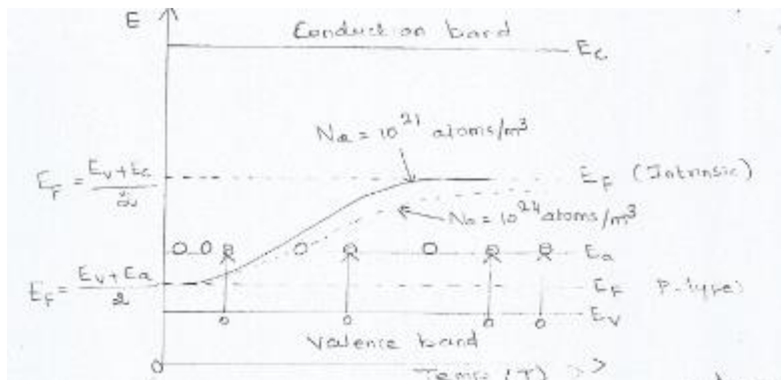
* At T = 0K, the above expression reduces to

$$E_F = \frac{E_v + E_a}{2}$$

So the Fermi level lies exactly half way between acceptor level and valence band.



* As the temperature increases, more and more acceptor atoms are ionized and Fermi level E_F shifts upwards.

* For a particular temperatures, all the acceptor atoms are fully ionized, where Fermi level crosses the acceptor level.

* Further increase in temperature results in generation of electron – hole pairs due to breaking of covalent bonds and the material tends to behave in an intrinsic manner.

* Therefore, Fermi level gradually moves towards intrinsic Fermi level E_f.

Variation of Fermi level with acceptor concentration:

* Rising of Fermi level from $E_F = \frac{E_v + E_a}{2}$, to intrinsic Fermi level with rise of temperature is slow in the case of higher acceptor concentration material than the lower concentration material.

* This is because highly doped semiconductor will behave in intrinsic manner only after all the acceptor atoms are ionized.

4. (a) Explain how the carrier concentration varies with temperature in a semiconductor.

(OR)

(b) Describe the variation of carrier concentration with temperature in an extrinsic Semiconductors.

The variation of the carrier concentration in an extrinsic semiconductor is explained by a graph drawn between $\log n$ and $\log p$ and $\frac{1}{T}$ the curve obtained is split into different ranges of temperatures.

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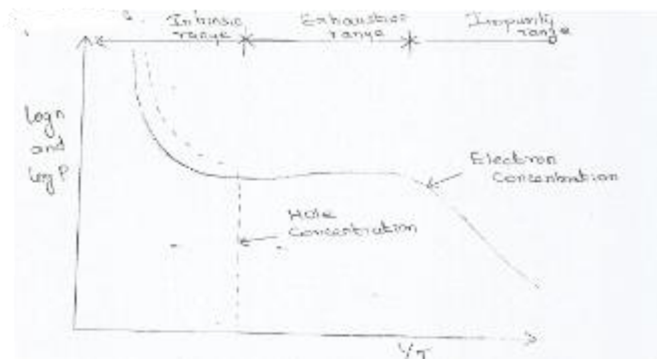

* At low temperature (T = 0K), both conduction and valence band are free from charge carriers.

* As temperature increases, the donor atoms get ionized and hence electron concentration in conduction band increases with temperature until all the donor atoms, are ionized. This range is known as impurity range.

* At room temperature, all the donor atoms are ionized and the concentration of the electrons remains constant over a certain temperature range. This range is known as exhaustion range.

* As the temperature is further increased, the thermal, ionization of the atoms in the valence band starts and the electrons in the valence band are lifted across the forbidden gap there by increasing the electron concentration in the conduction band considerably and the material practically becomes intrinsic and this range is called intrinsic range.

* The electron – hole pairs are created due to thermal energy in the intrinsic range. The hole concentration follows the dotted curve.

* As the temperature is increased, both the hole and electron concentration curves overlap since they become equal in number.

5. (a) Write a note on carrier transport in n-type and p-type semiconductors.

(OR)

(b) Explain carrier transport in n-type and p-type semiconductors.

<u>Carrier transport:</u>

In semiconductors, electron and holes are the carriers which move from one position to another and this movement of charge carriers is called carrier transport.

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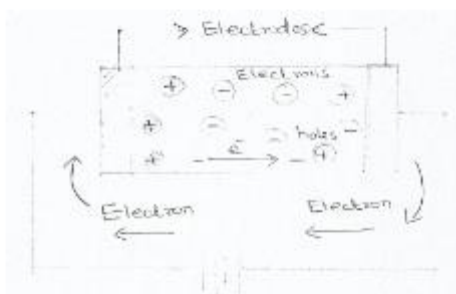
<u>Carrier transport in n-type semiconductor:</u>

Normally in an n-type semiconductor, electrons will be the majority charge carriers and holes will be the minority charge carriers. Apart from this, there exists equal number of immobile positive ions in n-type semiconductor.

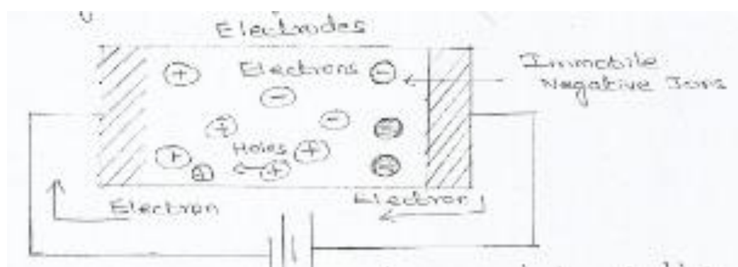
Consider an n-type semiconductor placed between a pair of electrodes for which a voltage is applied.

Due to the field applied, the electrons in the semiconductor move towards the positive terminal and they disappear. At the same time equal numbers of electrons are generated at the negative terminal. These electrons are attracted by the immobile positive ions present in the semiconductor and therefore a continuous flow of electron from one terminal to the other terminal takes place through the semiconductor depends on the biasing voltage.



Carrier transport in p – type semiconductor:

Normally in a p-type semiconductor, holes will be the majority charge carriers and electrons will be the minority charge carriers. Apart from this, there exists equal number of immobile negative ions in p-type semiconductors. Due to the field applied the holes in the semiconductor move towards the negative terminal and they combine with the electron coming out from the negative terminal and disappear.



Due to the field applied, the holes in the semiconductors move towards the negative terminal and they combine with the electrons coming out from the negative terminal and disappear. At the same time equal numbers of holes are generated near the positive terminal. These holes attract the immobile negative ions present in the semiconductor towards the positive terminal and thus causes, current to flow. During this process, an electron is lost by the acceptor atom and therefore it try to get back an electron from the adjacent atom to fill that hole in the semiconductor. This process continues and hole current occurs inside the semiconductor.

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6. (a) Derive an expression for drift transport and diffusion transport.

(OR)

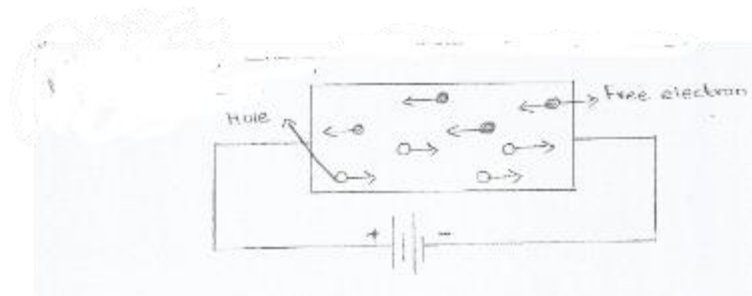
(b) Give a detailed account on drift and diffusion current.

When an electric field is applied, the net current flowing across a semiconductor has two types of transport,

(i) Drift transport
(ii) Diffusion transport

(i) Drift transport:

When an electric field is applied to a semiconductor, the electrons are attracted to the positive terminal and the holes are attracted to the negative terminal. The charge carriers are forced to move in a particular direction due to the field. This is known as drift motion and the net movement of charge carriers is termed as drift transport.



We know the current density, J = nev

The drift current density in a semiconductor due to electrons is

$J_e = nev_d$

But $v_d = \mu E$, $\therefore J_e = -ne\mu_e E$

The drift current density in a semiconductor due to holes is,

$J_h = pev_d$

$J_h = pe\mu_h E.$

The total drift current density,

$J_{drift} = J_e + J_h$

$= -ne\mu_e E + pe\mu_h E$

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For intrinsic semiconductor $n = p = n_i$

$J = -n_i e\mu_e E + n_i e\mu_h E$

$= n_i eE(\mu_h - \mu_e)$

$J = \sigma_i E$

$\sigma_i = n_i e (\mu_h - \mu_e)$

(ii) Diffusion transport:

In the case of N-type and p-type semiconductors, excess charge carriers may cause non-uniform distribution of charge carriers at some places.

When an electric field is applied, in addition to the drift motion, the charge carriers also move by diffusion at the places. The charge carriers move from the region of higher concentration to the regions of lower concentration in order to attain uniform distribution. This transport is called diffusion transport.

The concentration of charge carriers varies with respect to distance.

Rate of flow of electrons through unit area $\alpha \left(\frac{-dn}{dx}\right)$

The negative sign indicates the movement of charge carriers in the negative direction.

∴ Rate of flow of electrons through unit area = $-D_e \frac{dn}{dx}$

Where D_e is the proportionality constant and it is known as the diffusion constant for electrons.

The diffusion electron current density

J_n = charge of electron x Rate of flow of electrons.

$= (-e) \times - D_e \frac{dn}{dx}$

$= e\, D_e \frac{dn}{dx}$

Similarly, The diffusion hole current density

$J_p = e \times - D_h \frac{dp}{dx}$

$= -e\, D_h \frac{dp}{dx}$

Where D_p is the diffusion constant for holes.

The total diffusion current density

$J_{diffusion} = J_e + J_h$

$= e\, D_e \frac{dn}{dx} - e\, D_h \frac{dp}{dx}$

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Thus if an electric field is applied to the semiconductor, the total current contribution is due to both drift and diffusion transport.

i.e., $J_{total} = J_{drift} + J_{diffusion}$

$= ne\mu_e E + pe\, \mu_h E + e\, D_e \frac{dn}{dx} - e\, D_h \frac{dp}{dx}$

7. (a) (i) what is Hall effect? Obtain an expression for the Hall coefficient for a p-type Semiconductor.

(ii) Describe an experimental setup for the measurement of Hall voltage?

(iii) Explain any two Hall devices.

(OR)

(b) Explain Hall Effect with necessary theory. Describe an experiment to determine The Hall coefficient of a conducting material.

(OR)

(c) (i) Explain the phenomenon of Hall effect.

(ii) Derive an expression for Hall coefficient for an n-type semiconductor. Also state how Hall voltage is related.

(OR)

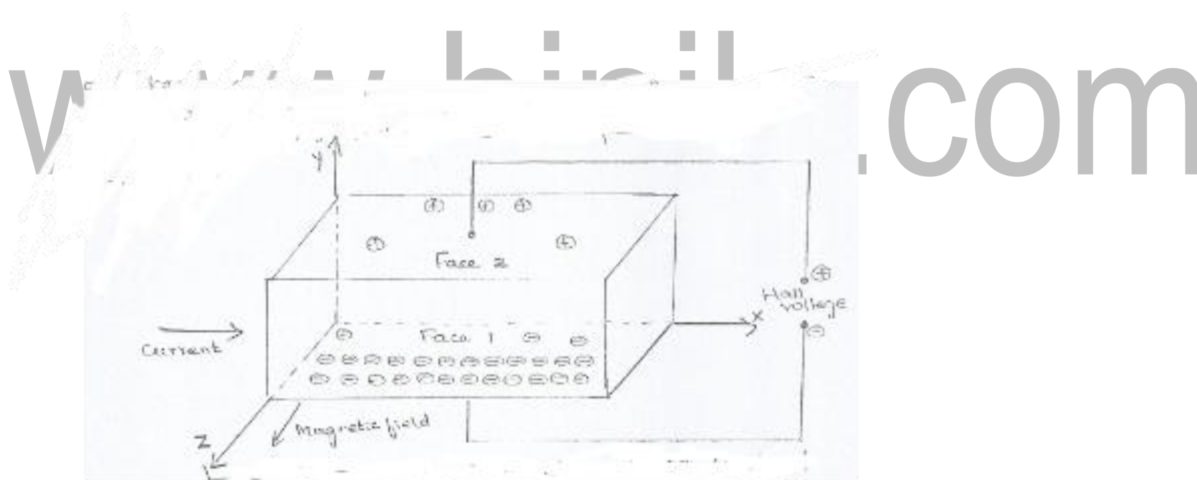
(d) What is Hall Effect? Show that for a p-type semiconductor the Hall coefficient R_H Is given by - $\frac{1}{pe}$. Describe an experimental setup to measure the Hall voltage.

When a piece of material (metal or semiconductors) carrying current is placed in a transverse magnetic field, an electric field is produced inside the conductor in a direction normal to both the current and the magnetic field. This phenomenon is called Hall Effect and the generated voltage is known as Hall voltage.

Hall Effect in N-type Semiconductor:

In n-type semiconductor, the current flow is entirely due to the flow of electrons moving from right to left.

Consider an N-type semiconductor material in the form of rectangular slab. Current flows in the X – direction and magnetic field in the Z – direction, as a result Hall voltage is developed along Y – direction.



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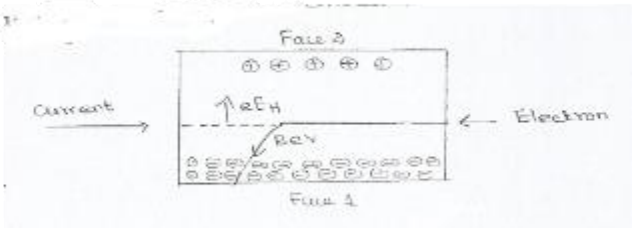
Let B be the magnetic field applied at right angle to the direction of current flow. The electrons moving with the velocity 'v' will experience a downward force –Bev, where e is the charge of the electron. This downward force deflects the electrons in the downward direction and there is an accumulation of negatively charged electrons on the bottom face of the slab. Hence this causes the bottom face to be more negative with respect to the top forces.

A potential difference is developed between top and bottom of the specimen which causes an electric field E_H called Hall field in the negative Y – direction. This field will give rise to a force - eE_H acting in the up word direction on each electron.



At equilibrium, the downward force 'Bev" will balance the upward force 'eE_H

$$-BeV = -eE_H$$

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

If n is the concentration of the electrons developed on face 1, e is the charge of electron and v is the velocity of electron, then the current density J is given by

$$J = -nev$$

$$\text{Hence, } V = -\frac{J}{ne} \text{ ------- } (2)$$

Sub eqn (2) in eqn (1) we gets

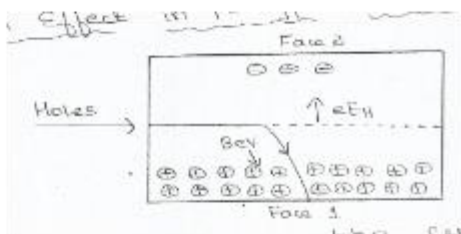
$$E_H = -\frac{BJ}{ne}$$

$$E_H = R_H \, JB \text{ ------- } (3)$$

$$\therefore \; R_H = \frac{E_H}{JB}, \text{ where } R_H = -\frac{1}{ne} \text{ (for electrons)}$$

'R_H' is called Hall coefficient or Hall constant. The negative sign indicates that the electric field is developed in the negative y-direction.

Hall Effect in p-type semiconductor:



In this case, the current flow is entirely due to the flow of positive holes from left and right.

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The current flow is along X-direction and the magnetic field is applied in the z-direction. Due to the applied magnetic field, the holes are accumulated in the bottom of the slab and thus produce a potential difference.

The force due to the potential difference is eE_H and the force due to magnetic field is Bev. At equilibrium,

$$Bev = eE_H$$

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

If p is the concentration of the holes 'e' is the charge of electron and 'v' is the velocity of electron, then the current density J is given by

$$J = peV$$

$$\text{Hence, } V = \frac{J}{pe} \text{ ------- } (2)$$

Sub eqn (2) in eqn (1) we get

$$E_H = \frac{BJ}{pe}$$

$$E_H = R_H BJ \text{ ------- } (3)$$

$$R_H = \frac{E_H}{BJ}, \text{ where } R_H = \frac{1}{pe} \text{ (for holes)}$$

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The positive sign indicates that the electric field is developed in the positive y-direction.

Hall coefficient in terms of Hall voltage:

If 'b' is the breadth of the sample across which Hall voltage V_H is measured.

$$E_H = \frac{V_H}{b}$$

$$V_H = E_H b$$

Substituting the value of E_H from eqn (3) we get

$$V_H = R_H JBb \text{ ------- } (4)$$

If't' is the thickness of the sample, area of the sample = breadth x thickness = bt

$$\text{Hence current density, } J = \frac{I}{bt}$$

Substituting this in eqn (4)

$$V_H = \frac{R_H IB}{t}$$

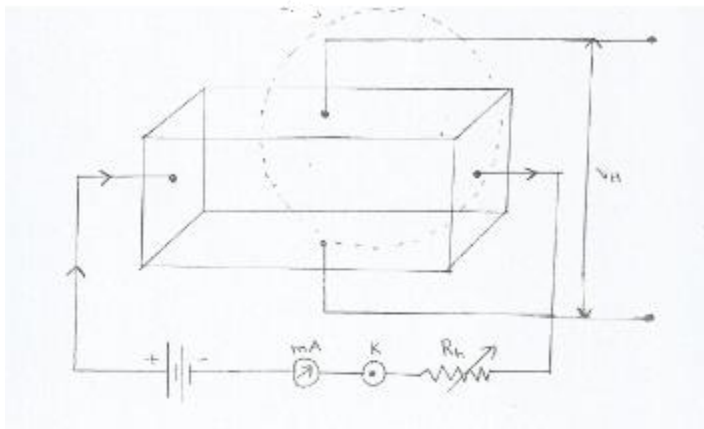
$$R_H = \frac{V_H t}{IB}$$

Experiment for determination of Hall coefficient:

A semiconductors material is taken in the form of a rectangular slab of thickness 't' and breadth 'b'. A suitable current I is allowed to pass through this sample along x-axis by connecting it to a battery. The sample is placed in between two poles of an electromagnet such that the applied magnetic field coincides with the z-axis. Hall voltage is developed in the sample is measured by fixing two probes at the cent of the bottom and top faces of the sample.

By measuring Hall voltage, Hall coefficient is calculated from the formula,

$$R_H = \frac{V_H}{IB}$$



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Application of Hall Effect:

(i) Determination of type of semiconductor.

(ii) Calculation of carrier concentration

(iii) Determination of mobility.

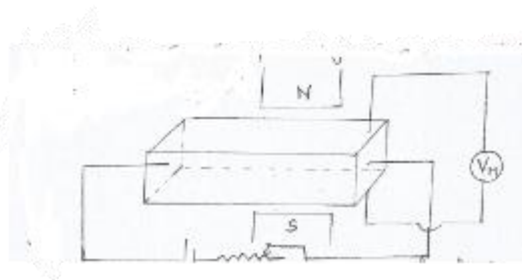
(iv) Measurement of magnetic flux density.

Hall Devices:

The devices which uses Hall Effect for its application is known as Hall devices. There are different types of devices to measure magnetic field, current, electrical power dissipated etc..,

(i) Gauss meter:

It is a type of sensor which senses the magnetic field.



A conductor or semiconductor is supplied with appropriate bias voltage and the Hall voltage is measured. When there is no magnetic field, the Hall voltage is zero. When it is subjected to magnetic field in the correct direction, a Hall voltage will appear indicating the presence of magnetic field. This sensor can be used to find magnetic field.

The voltmeter which is used to measure V_H is calibrated in terms of Gauss. Hence the name Gauss meter.

We know,

$$V_H = \frac{R_H IB}{t}$$

Here, R_H and t are constants. If I is kept constant, then $V_H \alpha B$.

(ii) Electronic Multiplier:

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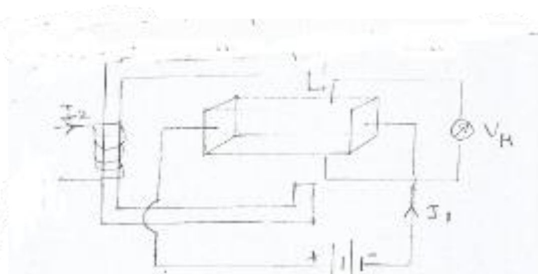
If the magnetic field to be sensed is generated by an electromagnet, then the device acts as electronic multiplier with the hall voltage being proportional to the product of the two currents.



Here V_H is a measure of two currents.

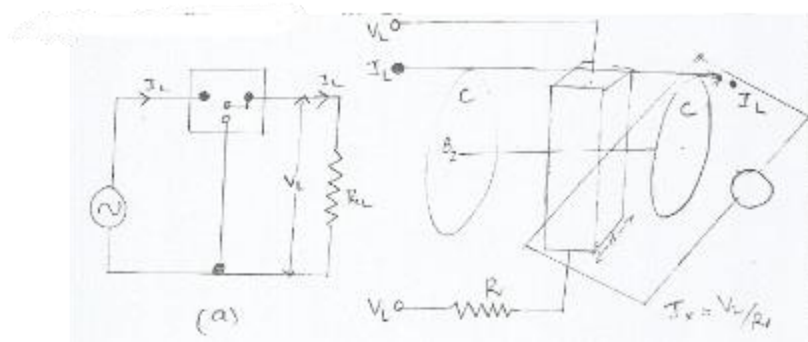
$$V_H \alpha BI_1$$

But $B \alpha I_2$

$$V_H \alpha I_1I_2$$

(iii) Electronic Wattmeter:

This instrument is used to measure electrical power dissipated in a load.



The load current I_L passes through two coils. Which are called current coils shown as c in fig (b). These coils set up a magnetic field B such that B α I_L. The Hall Effect sample of width'd' is positioned in this field between the coils.

The voltage across the load drives a current I = $\frac{V_L}{R}$ through the sample, where R is a series resistance which is larger than the resistance of the sample.

The Hall voltage measured is

$V_H = d\ E_H$

$= d\ R_H\ IB$

Or $V_H\ \alpha$ IB

Since, B α I_L and I α V_L

V_H α $I_L\ V_L$

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8. (a) With a neat sketch, describe the principle, construction and working of a schottky diode.

Give its advantages and disadvantages.

(OR)

(b) (i) With a neat sketch, describe the principle, construction and working of a schottky Diode.

(ii) Compare the V-I characteristics of schottky diode with PN junction diode.

(OR)

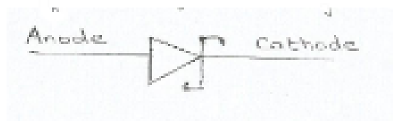
(c) Describe the construction and working of schottky diode and ohmic contact with neat Diagrams.

Schottky diode is a metal – semiconductor junction diode formed between a metal and moderately doped n-type semiconductor material.

In schottky diode, metals such as aluminium or platinum replace the p-type semiconductor. The metal acts as the anode and n-type semiconductor acts as the cathode.

Schottky diode is also known as schottky barrier diode, surface or hot carrier diode. They are widely used in radio frequency (RF) applications.

The symbol of schottky diode is



Working:

* When the metal is joined with the n-type semiconductors the conduction band electrons (free electrons) in the n-type semiconductors will move from n-type semiconductor to metal to establish an equilibrium state.

* The free electrons that are crossing the junction will provide extra electrons to the atoms in the metal. As a result, the atoms at the metal junction gains extra electrons and the atoms at the n-side junction loose electrons.

* The atoms that loose electrons at the n-side junction will become positive ions whereas the atoms that gain extra electrons at the metal junction will become negative ions. Thus, positive ions are created the n-side junction and negative ions are created at the metal junction called the depletion region.

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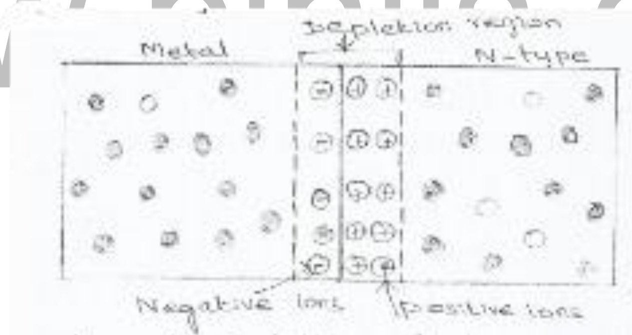

* In unbiased schottky diode, only a small number of electrons will flow from n-type semiconductor to metal.

* When a forward bias voltage is applied to the schottky diode, a large number of free electrons are generated in the n-type semiconductors and metal. However, the free electrons in n-type semiconductors and metal cannot cross the junction unless the applied voltage is greater than 0-2 volts. If the applied voltage is greater than 0-2 volts, the free electrons gain enough energy and overcome the built – in – voltage of the depletion region and current starts flowing through the schottky diode.

* If the applied voltage is continuously increased, the depletion region becomes very thin and finally disappears.

* When reverse bias voltage is applied to the schottly diode, the width of the depletion layer increases. As a result, the electric current stops flowing. However, a small leakage current flows due to the thermally excited electrons in the metal.

* If the reverse bias voltage is continuously increased, the electric current gradually increases due to the weak barrier.

* If the reverse bias voltage is largely increased, a sudden rise in electric current takes place which causes depletion region to break down which may permanently damage the device.

V – I Characteristics:

* The V-I characteristic of schottky diode is similar to the p-n junction diode. However,

The forward voltage drop of schottky diode is very low as compared to the p-n junction diode.

* The forward voltage drop of schottky diode is 0-2 to 0-3 volts whereas the forward voltage d of silicon p-n junction diodes is 0-6 to 0-7 volts.

* If the forward bias voltage is greater than 0.2 or 0.3 volts, electric current starts flowing through the Schottky diode.

* In Schottky diode, the reverse saturation current occurs at a very low voltage when compared to the silicon diode.

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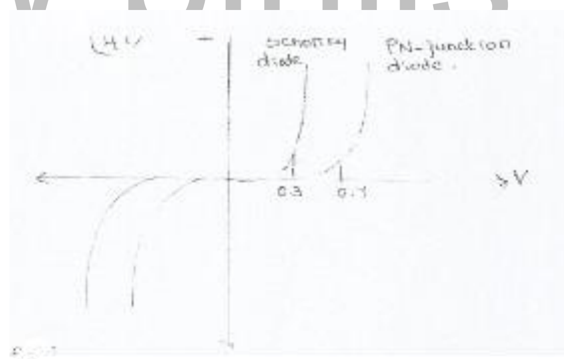

Advantages:

* Low forward voltage drop

* High current density

* Fast reverse recovery time.

* High efficiency

* Low junction capacitance

* Schottky diodes operate at high frequencies.

Disadvantages:

* Schottky diode produces large reverse saturation current than the p-n junction diode.

Applications:

* Schottky diodes are used as general – purpose.

* It are used in radio frequency (RF) applications.

* They are widely used in power supplies

* They are used to detect signals.

* They are used in logic circuits.

OHMIC CONTACTS

An ohmic contact is a non – rectifying electrical junction. The junction between two conductors which has a linear current – voltage curve that satisfy ohm's law is known as ohmic contact.

The ohmic contact is a low resistance junction that provides current conduction from metal to semiconductors and vice-versa.

When a metal and semiconductor are in intimate contact, there exists a potential barrier between the two which prevents most charge carriers from passing from one to the other. Only a small number of carriers have enough energy to get over the barrier and cross to the other material.

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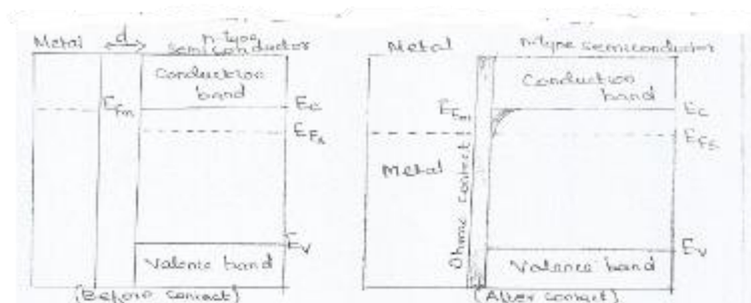


For a metal n-type semiconductor junction the surface of the metal is at positive potential and the surface of the semiconductors is at the negative potential. In this case, the electrons flow from the metal in to the semiconductor thus forming a positive surface charge layer in the metal.

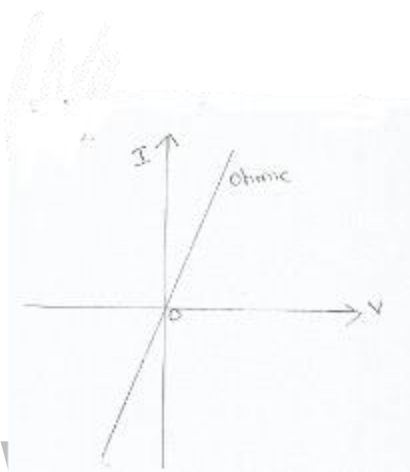
The resultant electric field set up an electric potential and the energy bands of the semiconductors bend downward. There is no barrier for the flow of electrons in both directions. Also, the Fermi levels of both are at the same level and there is no barrier potential.

Therefore, the current in the forward bias and reverse bias is always directly proportional to the applied voltage and follows ohm's law. Hence, this contact is called ohmic contact.

For a metal –n type semiconductor to act as ohmic contact, the work function of the metal should be less than that of n-type semiconductors.

For a metal p type semiconductor to act as ohmic contact, the work function of the metal should be greater than that of p-type semiconductor.

The V-I characteristics of ohmic contact is shown below.



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The choice of the metal and semiconductors for an effective ohmic contact between them should have

* Low contact resistance.

* Thermally stable

* Smooth morphology

* Compatible.

9. (a) Derive an expression for Einstein's Relation.

(OR)

(b) Obtain an expression for Einstein's Relation.

The relation between mobility and diffusion current of a semiconductor is known as Einstein's relation.

The drift current density due to electrons

J_n (drift) = $ne\mu_e E$

The diffusion current density due to electrons

J_n(diffusion) = e $D_n \frac{dn}{dx}$

At thermal equilibrium, drift current = diffusion current

$ne\mu_e E = e D_n \frac{dn}{dx}$

$neE = e \frac{D_n}{\mu_e} \frac{dn}{dx}$ ------- (1)

If F = eE is the force required to restore the excess charge carriers to equilibrium and to achieve uniform distribution of charge carriers, then the force due to 'n' electrons can be written as,

F = neE

Equation (1) becomes,

$F = e \frac{D_n}{\mu_e} \frac{dn}{dx}$ ------- (2)

From kinetic theory of gas, the force on excess of electrons due to diffusion is

$F = KT \frac{dn}{dx}$ ------- (3)

Comparing (2) and (3) we get

$KT \frac{dn}{dx} = e \frac{D_n}{\mu_e} \frac{dn}{dx}$

$KT = e\frac{D_n}{\mu_e}$ ------- (4)

Or $\frac{D_n}{\mu_e} = \frac{KT}{e}$ ------- (5)

Similarly for holes,

$\frac{D_p}{\mu_h} = \frac{KT}{e}$ ------- (6)

From eqn (5) and (6) we can write,

$\frac{D_n}{\mu_e} = \frac{D_p}{\mu_h}$

Or $\frac{D_n}{D_p} = \frac{\mu_e}{\mu_h}$

This relation is called Einstein's Relation.

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