UNIT – II
PART – A

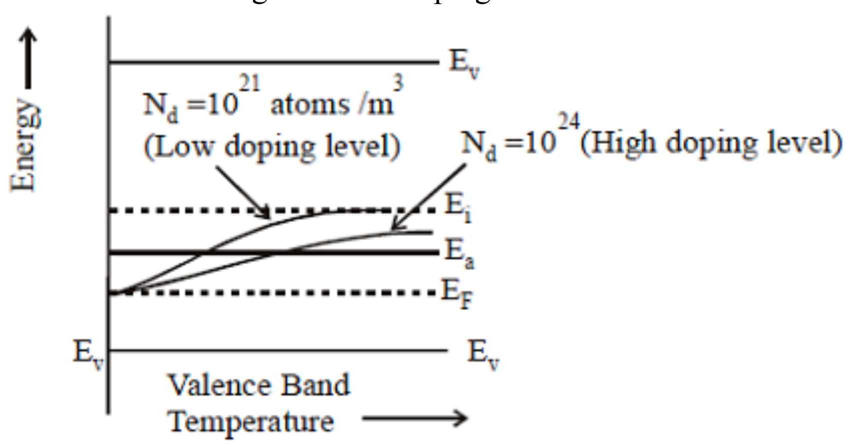
1. What are the differences between elemental semiconductors and compound semiconductors?

Elemental semiconductors	Compound semiconductors
They are made of single element. e.g. Ge, Si	They are made of single element. e.g. GaAs, Gap
Heat is produced due to recombination	Photons are emitted during recombination
current amplification is more	current amplification is less

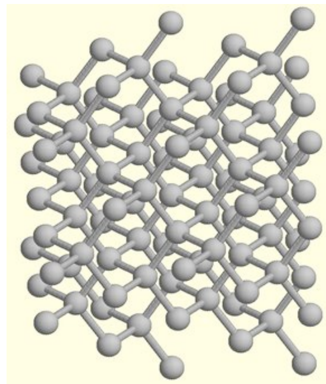
2. Write an expression for carrier concentration of holes in the valence band of p-type semiconductor.

$$\therefore p = (2N_a)^{1/2}\left[\frac{2\pi m_h^*}{h^2}\right]^{3/2} e^{-\Delta E/2kT}$$

3. Draw the diagram to show variation of Fermi level with temperature in the case of p-type semiconductor for high and low doping level.



4. What is covalent bond? Give the structure of a crystal having this bond.
   A covalent bond is a chemical link between two atoms in which electrons are shared between them.
   Diamond:

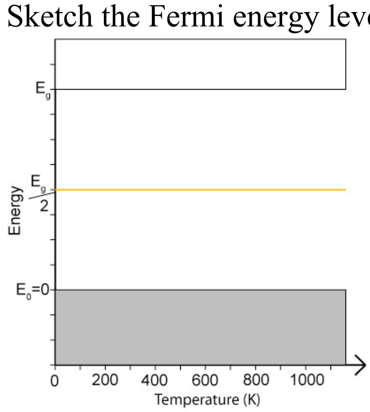


5. What is effective mass of an electron?
   The effective mass is a quantity that is used to simplify band structures by constructing an analogy to the behavior of a free particle with that mass.

6. Distinguish between n-type and p-type semiconductors.

n type semiconductors	**p type semiconductors**
It is obtained by doping an intrinsic semiconductor with pentavalent impurity.	It is obtained by doping an intrinsic semiconductor with trivalent impurity
It has donor energy level is very close to conduction band	It has acceptor energy levels very close to valence band.

7. Sketch the Fermi energy level of an intrinsic semiconductor.



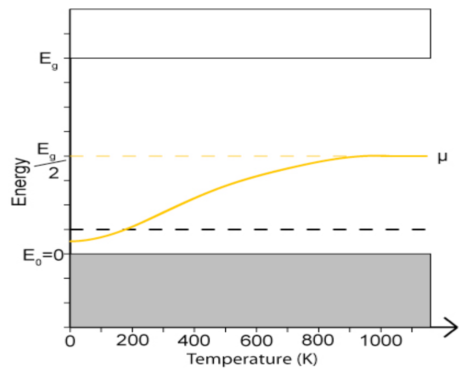
8. Given an extrinsic semiconductor , how will you find whether it is n-type or p-type.

By using hall coefficient R_H if it is positive then it is p-type and R_H is negative then it is n-type semiconductor.

9. Write an expression for electrical conductivity of an intrinsic semiconductor.

$$\sigma_i = 2e\left(\frac{2\pi kT}{h^2}\right)^{3/2}(m_e^* m_h^*)^{3/4} e^{\left(-E_g/_{2kT}\right)}(\mu_e + \mu_h)$$

10. Draw the graph for variation of Fermi level with temperature in p-type semiconductor.



PART – B

1. Derive and expression for carrier concentration in an intrinsic semiconductor. 16

We know, at 0K intrinsic semiconductor behaves as an insulator. But as temperature increases some electrons move from valence band to conduction band as shown in fig. 2.4. Therefore both electrons in conduction band and holes in valence bond will contribute to electrical conductivity. Therefore, the carrier concentration (or) density of electrons (n_e) and holes (n_h) has to be calculated.

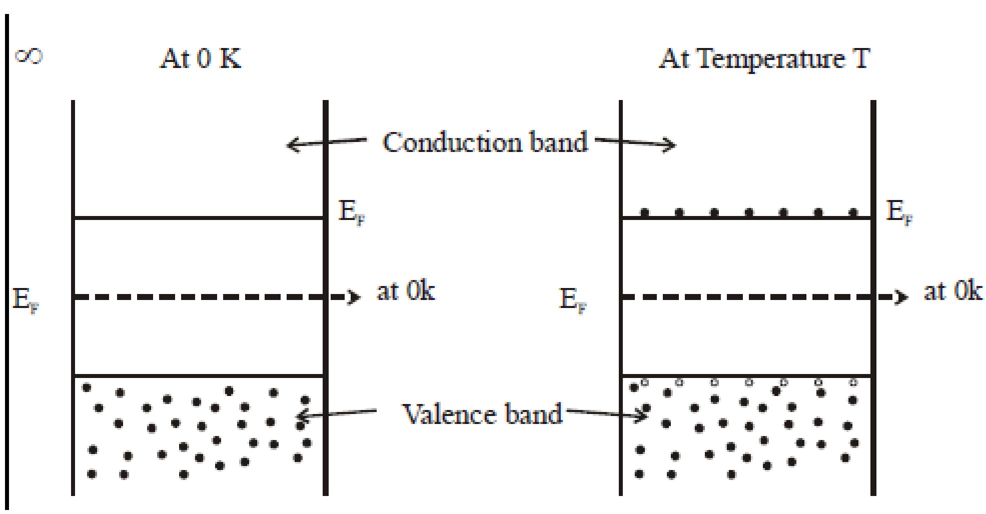


Fig. 2.4

Assume that electron in the conduction band is a free electron of mass m_e* and the hole in the valence band behaves as a free particle of mass m_n* . The electrons in the conduction band have energies lying from E_c to ∞ and holes in the valence band have energies from - to E_v as shown in fig. 2.4. Here E_c represents the energy of the bottom (or) lowest level of conduction band and E_v represents the energy of the top (or) the highest level of the valence band.

Density of Electrons in Conduction Band

Density of electrons in conduction band $n_e = {}_{E_c}^{\infty} Z(E).F(E)dE$ (2.1)

From Fermi-drac statistics we can write

$$Z\ E\ \ dE = 2.\frac{\pi}{4}\left(\frac{8m_e^*}{h^2}\right)^{1/2} E^{1/2}dE \tag{2.2}$$

Considering minimum energy of conduction band as E_c and the maximum energy can go upto we can write equation (2.2) as

$$Z\ E\ \ dE = \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{3/2}\ E - E_c\ ^{1/2}dE \tag{2.3}$$

We know from Fermi function, probability of finding an electron in a given energy state is

$$(F\ E) = \frac{1}{1+e^{(E-E_F)/K_BT}} \tag{2.4}$$

Substituting equation (2.4) and (2.3) in equation (2.1) we get density of electron in conduction band within the limits E_c to as

$$n_e = \frac{\pi}{2}\left\{\frac{8m_e^*}{h^2}\right\}^{3/2} \int_{E_c}^{\infty} \frac{(E-E_C)^{1/2}}{e^{(E-E_F)/K_BT}}.dE$$

$$n_e = \frac{\pi}{2}.\left\{\frac{8m_e^*}{h^2}\right\}^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2}.e^{(E_F-E)/K_BT} dE$$

Let us assume that

(or) $E = E_c + xK_BT$

Differencing we get $dE = K_BT.dx$

Limits: When $E = E_c : x = O$

$\therefore$ When

Limits are 0 to

Equation (2.6) can be written as

$$n_e = \frac{\pi}{2}.\left\{\frac{8m_e^*}{h^2}\right\}^{3/2} \int_{0}^{\infty} (xK_BT)^{1/2}.e^{(E_F-xK_BT-E_c)/K_BT} K_BT\ dx$$

$$n_e = \frac{\pi}{2}.\left\{\frac{8m_e^*}{h^2}\right\}^{3/2} \int_{0}^{\infty} x^{1/2}(K_BT)^{3/2}.e^{(E_F-E_c)/K_BT} e^{-x} dx$$

$$n_e = \frac{\pi}{2}\cdot\left\{\frac{8m_e^*}{h^2}\right\}^{3/2} e^{(E_F-E_c)/K_BT}\int_0^\infty x^{1/2}.e^{-x}dx$$

$$n_e = \frac{\pi}{2}.\left\{\frac{8m_e^*K_BT}{h^2}\right\}^{3/2} e^{(E_F-E_c)/K_BT}\frac{\sqrt{\pi}}{2}$$

$$\left(\text{Since}\int_0^\infty x^{1/2}e^{-x}dx = \frac{\sqrt{\pi}}{2}\right)$$

$$n_e = \frac{1}{4}\ \frac{8\pi m_e^*K_BT}{h^2}^{\ 3/2} e^{(E_F-E_c)/K_BT}$$

Density of Holes in Valence Band

We know, F(E) represents the probability of filled state. As the maximum probability will be 1, the probability of unfilled states will be [1 - F (E)].

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Example, If F(E) = 0.2 then 1 - F (E) = 0.8

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i.e., 20% chance of finding an electron in conduction band and 80% chance of finding a hole in valence band.

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n_e)

Let the maximum energy in valence band be E_v and the minimum energy be $-$. Therefore density of holes in valence band n_h is given by

upto we can write equation (2.2) as

$$Z\ E\ \ dE = \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{3/2}\ E-E_c\ ^{1/2}dE \qquad (2.3)$$

$$n_h = \int_{-\infty}^{E_v} Z(E)\,[1-F(E)]\,dE \qquad (2.8)$$

We know $$Z(E)\,dE = \frac{\pi}{2}\left\{\frac{8m_h^*}{h^2}\right\}^{3/2}(E_v - E)^{1/2}\,dE \qquad (2.9)$$

Limits: When $E = -\infty$

We have

$$E_v - (-\infty) = x$$

When

$\therefore$ Limits are to 0

Equation (2.11) becomes

$$n_h = \frac{\pi}{2}\;\frac{8m_h^*}{h^2}^{3/2}\int_{\infty}^{0}(xK_BT)^{1/2}\,.\,e^{(E_v - xK_BT - E_F)/K_BT}(-K_BT)\,dx$$

$$n_h = \frac{1}{4}\;\frac{8\pi m_h^* K_BT}{h^2}^{3/2} e^{(E_v - E_F)/K_BT}$$

Variation of Fermi energy level and carrier concentration with temperature in an intrinsic semicoductor

For an intrinsic semiconductor number of electrons (i.e.) electron density will be the same as that of number of holes (i.e.,) hole density.

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(i.e.,) $n_e = n_h$

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Equating equations (2.7) and (2.12), we can write

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Let the maximum energy in valence band be E_v and the minimum energy be –

. Therefore density of holes in valence band n_h is given by

upto we can write equation (2.2) as

$$Z(E)\,dE = \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{3/2}(E - E_c)^{1/2}\,dE \qquad (2.3)$$

$$m_e^{*\,3/2}\, e^{(E_F - E_c)/K_BT} = m_h^{*\,3\backslash 2}\, e^{(E_v - E_F)/K_BT} \qquad \left\{\frac{m_h^*}{m_e^*}\right\}^{3/2} = \frac{e^{(E_F - E_c)/K_BT}}{e^{(E_v - E_F)/K_BT}}$$

ne

$$3/2\ \log\left(\frac{m_h^*}{m_e^*}\right) = \frac{[2E_F - (E_v + E_c)]}{K_BT}$$

$$2E_F = E_c + E_v + \frac{3}{2} K_BT \log\left(\frac{m_h^*}{m_e^*}\right)$$

$$E_F = \frac{E_c + E_v}{2} + \frac{3}{4} K_BT\ \log\left(\frac{m_h^*}{m_e^*}\right)$$

$\therefore$ Density of electrons in conduction band is

$$n_e = 2\ \frac{2\pi m_e^* K_BT}{h^2}^{3/2}\ e^{(E_F - E)/K_BT} \qquad \rightarrow (2.7)$$

If

$\therefore$ Equation (2.13) becomes

$$E_F = \frac{(E_c + E_v)}{2}$$

i.e., the Fermi nergy level lies in the midway between E_c and E_v as shown in fig. 2.5. (since at 0K, $K_BT = 0$)

But in actual case $m_h^* > m_{e^*}$ and the Fermi energy level slightly increases with the increase in temperature as shown in fig. 2.5.

2. i) Derive an expression for the electrical conductivity of an intrinsic semiconductor. 6

We know that $\sigma = ne\mu$

Electrical conductivity of a semiconductor due to electrons is

$\sigma_e = ne\mu_e$ (1)

n is number of electrons per unit volume

e is charge of an electron (1.6 X 10^{-19} C)

μ_e is mobilty of electrons

Similarly $\sigma_h = pe\mu_h$ (2)

Electrical conductivity of semiconductor $\sigma_i = \sigma_e + \sigma_h$ (3)

Substitute equation (2) & (3) in equation (3)

$\sigma_i = e(n\mu_e + p\mu_h)$ (4)

In intrinsic semiconductor $n=p=n_i$

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

$\sigma_i = e\, n_i\, (\mu_e + \mu_h)$ (5)

$$\sigma_i = 2\left(\frac{2\Pi kT}{h^2}\right)^{\frac{3}{2}} (m_e m_h)^{\frac{3}{4}} e^{\frac{-E_g}{2kT}}\, e(\mu_e + \mu_h)$$

$$\sigma_i = 2e\left(\frac{2\Pi kT}{h^2}\right)^{\frac{3}{2}} (m_e m_h)^{\frac{3}{4}} e^{\frac{-E_g}{2kT}}\, (\mu_e + \mu_h) \qquad (6)$$

So electrical conductivity depends upon the negative exponential of the forbidden gap and also mobilities of an electron and holes

ii) Discuss the variation of Fermi level with temperature in an intrinsic semiconductor. 6

2.4.4. Variation of Fermi energy level and carrier concentration with temperature in an intrinsic semicoductor

For an intrinsic semiconductor number of electrons (i.e.) electron density will be the same as that of number of holes (i.e.,) hole density.

(i.e.,) $n_e = n_h$

Equating equations (2.7) and (2.12), we can write

$$m_e^{*\,3/2}\, e^{(E_F - E_c)/K_BT} = m_h^{*\,3\backslash 2}\, e^{(E_v - E_F)/K_BT} \qquad \left\{\frac{m_h^*}{m_e^*}\right\}^{3/2} = \frac{e^{(E_F - E_c)/K_BT}}{e^{(E_v - E_F)/K_BT}}$$

$$= e^{(E_F - E_c - E_v + E_F)/K_BT}$$

Taking log on both sides we have

$$3/2\ \log\left(\frac{m_h^*}{m_e^*}\right) = \frac{\left[2E_F - \left(E_v + E_c\right)\right]}{K_B T}$$

$$2E_F = E_c + E_v + \frac{3}{2} K_B T \log\left(\frac{m_h^*}{m_e^*}\right)$$

$$E_F = \frac{E_c + E_v}{2} + \frac{3}{4} K_B T \log\left(\frac{m_h^*}{m_e^*}\right)$$

If

$\therefore$ Equation (2.13) becomes

$$E_F = \frac{(E_c + E_v)}{2}$$

i.e., the Fermi nergy level lies in the midway between E_c and E_v as shown in fig. 2.5. (since at 0K, $K_B T = 0$)

But in actual case $m_h^* > m_{e^*}$ and the Fermi energy level slightly increases with the increase in temperature as shown in fig. 2.5.

iii) How will you determine the energy gap of an intrinsic semiconductor? 4

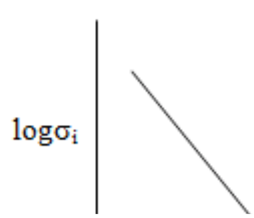
$$\sigma_i = n_i e(\mu_e + \mu_h)$$

$$\sigma_i = 2e\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{\left(-E_g/2kT\right)}(\mu_e + \mu_h)$$

$$\sigma_i = Ce^{-E_g/2kT}$$

Taking log on both sides

$$\log\sigma_i = \log C - {E_g}/{2kT}$$



Determination of E_g:

$$\sigma_i = Ce^{-E_g/2kT}$$

$$\rho_i = 1/\sigma_i = \frac{1}{C}\,e^{E_g/2kT}$$

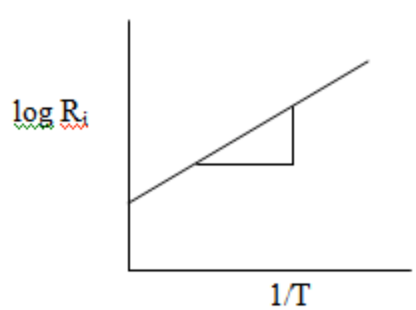
$$\rho_i = \frac{R_i a}{l} = \frac{1}{C}\,e^{E_g/2kT}$$

$$R_i = \frac{l}{aC}\,e^{E_g/2kT}$$

$$R_i = C_1\,e^{E_g/2kT}$$

$$logR_i = \log C_1 + E_g/2kT$$

This is similar to the equation of a straight line, whose slope is given by $E_g/2k$



Therefore E_g = 2k x slope.

3. i) Derive expressions for carrier concentration and Fermi energy in a n-type semiconductor. 10

2.5 EXTRINSIC SEMICONDUCTORS

2.5.1. Carrier concentration in N-type semiconductor

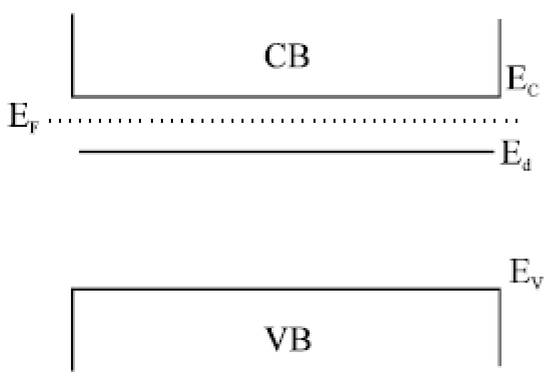


Fig. 2.8

Let be the number of donor levels per unit volume of energy E_d lying below the conduction band. At low temperatures small fraction of donors will be ionized and practically all donor levels will be filled.

When E_C-$E_F > 4k_BT$, the density of electrons in the conduction band will be,

$\rightarrow (2.19)$

If we assume $E_F - E_d >> 4k_BT$, (above the donor level), then the density of empty donor level is,

$$\log_e 2\left(\frac{2\pi m_e^* k_BT}{h^2}\right)^{3/2} + \frac{E_F - E_C}{k_BT} = \log_e N_d + \frac{E_d - E_F}{k_BT}$$

Taking natural logarithm on both sides, we get,

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

$$\frac{2E_F - E_C - E_d}{k_BT} = \log_e \frac{N_d}{2}\left(\frac{2\pi m_e^* k_BT}{h^2}\right)^{-\frac{3}{2}}$$

$$\therefore E_F = \frac{E_C + E_d}{2} + \frac{K_BT}{2}\log_e \frac{N_d}{2}\left(\frac{2\pi m_e^* k_BT}{h^2}\right)^{-\frac{3}{2}}$$

E_F

$$E_F = \frac{E_C + E_d}{2}$$

At T = 0 K,

i.e., At absolute zero, the Fermi level lies exactly half way between the donor level and bottom of the conduction band. As the temperature increases, the Fermi level falls below the donor level and it approaches the center of forbidden gap which makes the substance an intrinsic semiconductor. This gives a limit on the operating temperature of a semiconducting device. Fig. (2.9) shows the variation of Fermi level with temperature in n-type and p-type semiconductors. The effect of donor and acceptor concentrations also is shown.

Substituting the value of from eqn. (2.20) in eqn. (2.19), the electron density in the conduction band can be obtained. Consider the term,

$\therefore$ The electron density in the conduction band,

$$n = 2 \;{\frac{2\pi m_e^* k_B T}{h^2}}^{\frac{3}{2}} \left[\frac{N_d}{2}\right]^{\frac{1}{2}} \left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{-\frac{3}{4}} \exp\left[\frac{E_d - E_C}{2k_B T}\right]$$

$$\text{i.e.,}\quad n = \sqrt{2N_d}\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{\frac{3}{4}} \exp\left[\frac{E_d - E_C}{2k_B T}\right]$$

Eqn. (2.21) shows that the density of electrons in the conduction band is proportional to the square root of the donor concentration.

Similarly the density of holes in the p-type semiconductor can be derived as,

$$p = \sqrt{2N_a}\;{\frac{2\pi m_h^* k_B T}{h^2}}^{\frac{3}{4}} \exp\left[\frac{E_V - E_A}{2k_B T}\right] \qquad (2.22)$$

ii) Explain the variation of Fermi level with temperature and donor impurity concentration. 6

2.5.2. Variation of Fermi level and carrier concentration with temperature and impurities in 'n'-Type semiconductor

When the temperature is increased some electrons in E_d level may be shifted to conduction band and hence some vacant sites will be created in E_d levels. Therefore the Fermi level shifts down to separate that empty levels and the filled valence band level as shown in fig. 2.10, for the doping level of N_d 10^{21} atoms / m^3

From the fig 2.10 it can be seen that for the same temperature, if the impurity atoms i.e., doping level is increased ($N_d = 10^{24}$ atoms/m^3), the electron concentration increases and hence the Fermi level increases.

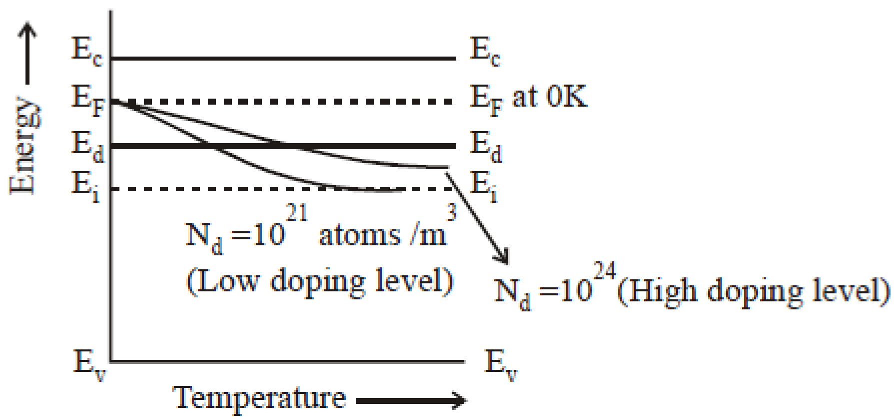


Fig. 2.9

4. i) Derive expressions for carrier concentration and Fermi energy in a p-type semiconductor. 10

2.5.3. P-type semiconductor

When a small amount if trivalent impurity is added to a pure semiconductor, it becomes P-types semiconductor.

The trivalent impurity provides a large number of holes in the semiconductor.

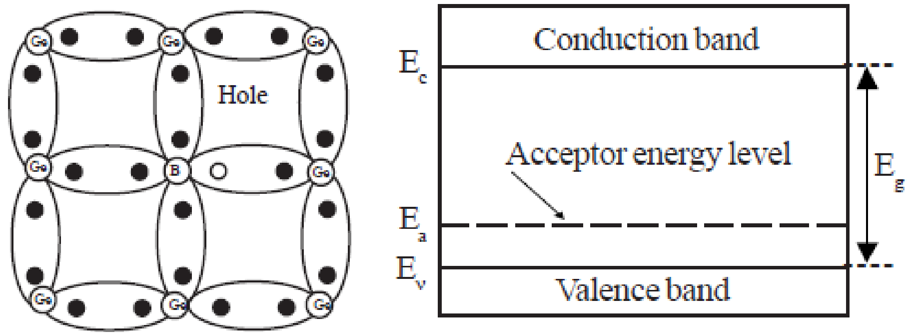
Typical examples of trivalent impurities are gallium (Atomic no.31) and indium (Atomic no. 49). Such impurities are known as acceptor impurities because the holes they create can accept electrons.

To a pure semiconductor (germanium) having 4 valence electrons, if a trivalent impurity (boron) having '3' valence impurity is added, then 3 valence electrons of trivalent impurity form a covalent bond with three valence electrons of germanium. The fourth electron is unable to form a covalent bond.The incomplete covalent bond being short if one electron (missing electron) is called a hole.

Every trivalent atom contributes one hole in addition to thermally generated electron-hole pairs. Therefore, the number of holes is more than the number of electrons (fig. 2.10 (a)).

The addition of trivalent impurity creates a large number of holes (positive charge carries) in the semiconductor and hence called P-type semiconductor where p stands for positive type. Moreover, holes are majority charge carries and electrons are minority charge carries.

In this case, the allowable energy level (acceptor energy level) is created just above the valence band (fig. 2.10 (b). A very small amount of energy is needed for an electron to enter the acceptor energy level. Thus a number of holes is generated in the valence band, In other words, a large number of positive charge carries are created.



(a) (b)

Fig. 2.10 P-type semicondutor : (a) crystal structure
(b) energy hand diagram

2.5.4. CONCENTRATION OF HOLES IN THE VALENCE BAND P-TYPE SEMICONDUCTOR (Derivation)

In p-type semiconductor, the accepter level is just above the valence band (fig. 2.11). Let E_a represent the energy of the acceptor level and N_a denote the number of acceptor atoms per unit volume.

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

$$P = 2\left[\frac{2\pi m_n^* kT}{h^2}\right]^{3/2} e^{(E_v - E_F)/kT}$$

where E_F is Fermi energy level; E_v is the energy corresponding to the top of valence band.

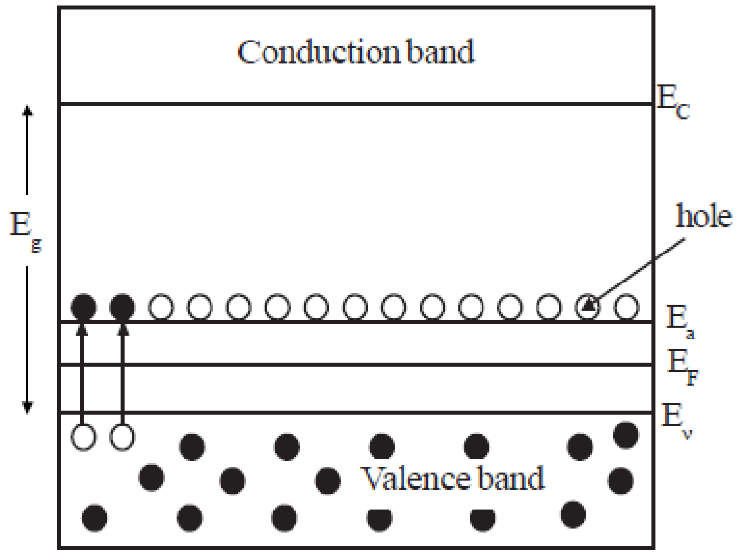


Fig. 2.11 Energy band diagram for P-type semiconductor

Density of ionised acceptors

$$= N_a F(E_a) = \frac{N_a}{1 + e^{(E_a - E_F)/kT}} \quad \text{----}(2)$$

Since $E_a - E_F >> kT$, $e^{(E_a - E_F)/kT}$ may be a large quantity, and thus '1' can be neglected from the denominator of R.H.S. of equation (2).

Density of ionised acceptors = Na $e^{(E_F - E_a)/kT}$ --- (3)

At equilibrium

Density of holesin the valence band = Density of ionised acceptors

Taking log on both sides of equation (4), we have

$$\log_e\left[2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}\right] + \frac{E_v - E_F}{kT} = \log N_a + \frac{E_F - E_v}{kT}$$

Rearranging, we get

$$\frac{E_F - E_v - E_v - E_F}{kT} = \log N_a \log\left[2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}\right]$$

or $$\frac{2E_F - (E_a - E_v)}{kT} = -\log\left[\frac{N_a}{2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}}\right]$$

or $$2E_F - (E_a - E_v) - kT\log\left[\frac{N_a}{2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}}\right] \quad \text{----(5)}$$

$$\therefore E_F = \frac{E_a + E_v}{2} - \frac{kT}{2}\log\left[\frac{Na}{2\left[\frac{2\pi m_h^*}{h^2}\right]^{3/2}}\right] \quad \text{---- (6)}$$

Substituting the expression of E_F from (6) in (1), we get

$$p = 2\left[\frac{2\pi m_h^*}{h^2}\right]^{3/2} \exp\left\{\frac{\left[\frac{E_v + E_a}{2} - \frac{kT}{2}\left[\frac{Na}{2\left[\frac{2\pi m_h^*}{h^2}\right]^{3/2}}\right]\right]}{kT}\right\}$$

$$p = 2\left[\frac{2\pi m_h^*}{h^2}\right]^{3/2} \exp\left[\frac{2E_v - E_v - E_a}{2kT}\right] \log\left[\frac{Na}{2\left[\frac{2\pi m_h^*}{h^2}\right]^{3/2}}\right]$$

$$p = 2\left[\frac{2\pi m_h^*}{h^2}\right]^{3/2} \frac{\left(\frac{Na}{2}\right)^{1/2}}{2\left[\frac{2\pi m_h^*}{h^2}\right]^{3/4}} e^{(E_v - E_a)\backslash 2kT}$$

$$\therefore p = (2N_a)^{1/2}\left[\frac{2\pi m_h^*}{h^2}\right]^{3/2} e^{(E_v - E_a)/2kT} \qquad \text{----- (7)}$$

If we put E_a-E_v = ΔE, equation (7) becomes

The concentration of hole in a p-type semiconductor is given by

$$\boxed{\therefore p = (2N_a)^{1/2}\left[\frac{2\pi m_h^*}{h^2}\right]^{3/2} e^{-\Delta E/2kT}} \qquad \text{---- (8)}$$

It is clear from equation (8) that the density of holes in the valence band is proportional to the square root of acceptor concentration.

ii) Explain the variation of Fermi level with temperature and acceptor impurity concentration. 6

When the temperature is increased,some of the electrons in the valence band will go to acceptor energy levels by breaking up the covalent bonds and hence the Fermi energy level is shifted in upward direction for doping level $N_d=10^{21}$ atoms/m^3 as shown figure.

2.12.

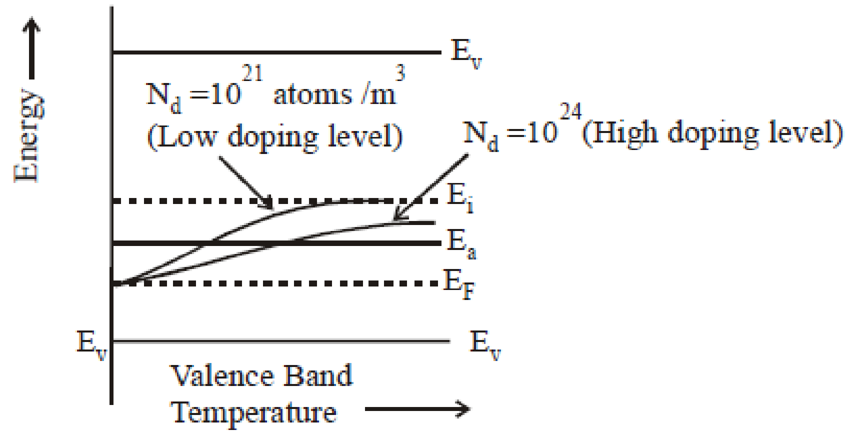
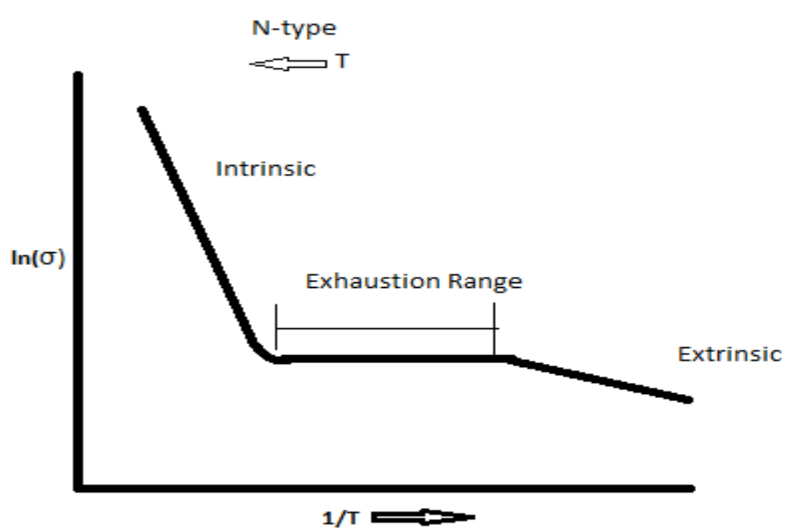


Fig. 2.12

From the fig. 2.12 it can be seen that for the same temperature, if the impurity atoms (i.e.,) doping level is increased say $N_a = 10^{24}$ atoms/m^3 the hole concentration increases and hence the Fermi level decreases.

Therefore at low temperature the Fermi energy level may be increased upto the level of intrinsic energy level (E_i)

5. i) How does the carrier concentration and electrical conductivity vary with temperature in an extrinsic semiconductor? Explain. 8



At low temperatures, the charge carriers are mainly due to the impurity atoms. The low temperature is sufficient to form electrons in the conduction band from the donor levels in n-type semiconductors. This region, where the charge carriers are due to impurity atoms is called **extrinsic or impurity range.**

As temperatures increase, all the electrons in the donor levels are ionized and no more additional electrons are obtained for a certain range of temperatures, as the temperature is not sufficient to move electrons from valence band to the conduction band. Here the carrier concentration is nearly constant and this region is called **exhaustion region**.

When the temperature increases the electrons from the valence band move to the conduction band forming electron hole pairs. This mechanism is identical to the working of an intrinsic semiconductor and this region is called **intrinsic range.**

ii) The energy gap of Si is 1.1 eV. Its electron and hole mobilities at room temperature are 0.48 and 0.013 m^2 /V-s. Evaluate its conductivity. 8

$$n_i = 2\left(\frac{2\Pi kTm_e}{h^2}\right)^{\frac{3}{2}} e^{\frac{-E_g}{2K_b}T}$$

$$n_i = 2\left(\frac{2X3.14xXX300X9.1X10^{-31}}{6.626X10^{-34\,2}}\right)^{\frac{3}{2}} e^{\frac{-1.1}{2X\,1.38X10^{-23}}X\left(\frac{300}{1.6X10^{-19}}\right)}$$

n_i= 1.4707X10^{16} m^{-3}

σ_i=e n_i (μ_e+μ_h)=1.4707X10^{16}X1.6X10^{-19}X(0.48+0.013)=1.160X10^{-3} $\Omega^{-1}m^{-1}$

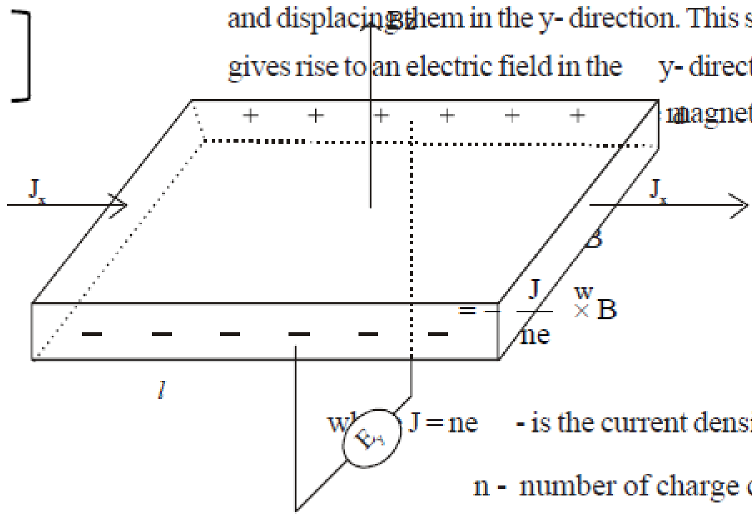
6. i) What is Hall effect? Explain Hall effect in p - type and n- type semiconductors. Derive an expression for Hall coefficient. 2+6+4

2.6. HALL EFFECT

Consider a specimen in the form of rectangular cross-section carrying a current of density J in the x- direction. If a constant magnetic field B is applied along the z- direction, it is found that an emf develops in a direction perpendicular to both of these. i.e., along the y-direction.This voltage is called the **Hall voltage** and the effect is **Hall effect**.

The Hall effect refers to the production of transeverse electric field when a current carrying conductor is placed right angle to the applied magnetic field. It gives the information of the sign of the charge carrier.

Fig. 2.13 Hall effect (n-type semiconductor)



The magnetic induction B exerts a force on the charged particles carrying current and displacing them in the y- direction. This sets up a non-uniform charge density, which gives rise to an electric field in the y- direction. In equilibrium the force due to this field magnetic field.

$$= -\frac{J}{ne} \times B$$

where J = ne - is the current density

n - number of charge carriers per unit volume

Now, $E = -R_H (J \times B)$

where R_H is the **Hall coefficient**

$$R_H = -\frac{1}{n|e|} \quad (\text{or}) \quad R_H = \frac{E_y}{J_x B_z}$$

The negative sign in eqn. (2.23) implies that we would expect R_H to be negative for electrons of negative charge.

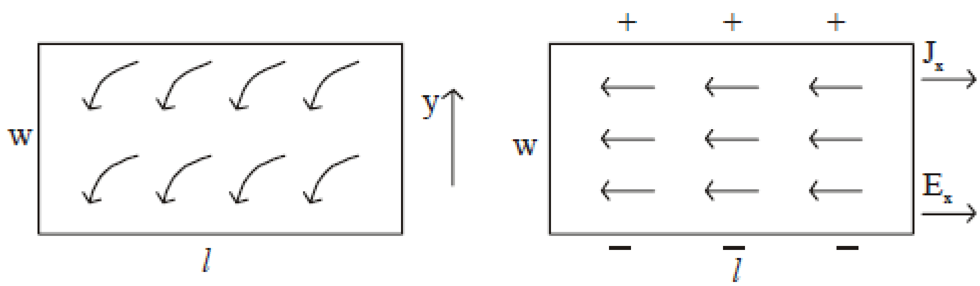
Gernerally, when relaxation time is dependent on velocity, then,

$$R_H = -\frac{3\pi}{8} \frac{1}{n|e|}$$

ii) Describe the experimental setup for the measurement of Hall voltage and give its applications. (4)

Experiment

In measuring the voltage due to the Hall effect, a rectangular strip whose thickness and width are small compared with the length is used as shown in fig. (2.11). The x- axis is taken along the strip (length) and y- axis along the width. Hall effect is observed by measuring the transverse voltage set up across the strip. This is the external voltage required to make the current flow entirely in x- direction (fig. 2.14 (a) and 2.14 (b)).



(a) Drift velocity just started (b) Drift velocity in steady state

Fig. 2.14 Section perpendicular to z-axis

Results :

1. In an intrinsic semiconductor, the Hall co-efficient will not vanish, even though there are equal number of holes and electrons.

   The general expression for intrinsic semiconductor

   is the mobility ratio.Since $\mu_e > \mu_h$; $b > 1$

   Thus the electron conduction predominates in the intrinsic semiconductor.

2. Most of the monovalent metals have negative Hall co-efficient. But for elements like Zn and Cd, R_H is positive. According to band theory of solids, a material with nearly filled valence band can give rise to negative electron mass conduction or hole conduction. Due to the possible hole conduction Zn and Cd have positive R_H.

Applications of Hall effect

1. Determination of semiconductor type

For a n-type semiconductor, Hall coefficient is negative, whereas for a p-type semiconductor it is positive. Thus, the sign if the Hall coefficient is used to determine whether a given semiconductor is n-type or p-type.

2. Calculation of carrier concentration

By measuring hall coefficient RH, carrier concentration can be obtained from

$$n = \frac{1}{eR_H}$$

3. Determination of mobility

We know that electrical conductivity, $\sigma_e = ne\mu_e$.

Hence, $\mu_e = \frac{\sigma_e}{ne}$

or $\mu_e = \sigma_e R_H$

Thus, by measuring electrical conductivity and Hall coefficient of a sample, the mobility of charge carries can be calculated.

4. Magnetic field meter

Hall voltage V_H for a given current is proportional to B. Hence V_H measures the magnetic field B.

5. Hall effect multiplier

This instrument can give an output proportional to the product of two signals. Thus, if current I is made proportional to one input and if B is proportional to the second input, then hall voltage V_H is proportional to the product of two inputs.

7. i) A magnetic flux density of 0.5 Wb/m^2 is applied from front to back, perpendicular to largest faces of a specimen. A current of 20 mA flows lengthwise and the voltage measured across its width is 37 µV. The specimen is 12 mm long, 1 mm wide and 1 mm thick. Find the Hall coefficient. 5

$R_H = V_H b / I_H B = 37 \times 10^{-6} \times 1 \times 10^{-3} / 20 \times 10^{-3} \times 0.5 = 3.7 \times 10^{-6}\ C^{-1}m^3$

$N = 1.18 / e R_H = 1.18/1.609 \times 10^{-19} \times 3.7 \times 10^{-6} = 1.98 \times 10^{24} /\ m^3$

ii) Explain how a semiconducting material can be classified into p-type and n-type semiconductor using Hall coefficient. 5

$R_H = \frac{1.18}{pe}$ and it is positive value for holes

$R_H = \frac{1.18}{ne}$ and it is negative value for electrons

iii) The donor density of an n-type germanium sample is $10^{21} / m^3$. The sample is arranged in a Hall experiment having the magnetic field of 0.5 tesla and its current density is 500 A/m^2.Find the Hall voltage if the sample 3mm wide. 6

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

$$= \frac{1}{10^{21}\, 1.6X10^{-19}} = 6.25X10^{-3}$$

Hall Voltage $V_H = R_H J_X Bt = 6.25X10^{-3} X500X0.5X3X10^{-3} = 4.6875X10^{-3}$ volts

8) i)Calculate the intrinsic carrier concentration of charge carriers of Ge at 300 K.E_g for Ge is 0.67 eV.Given $\frac{m_e^*}{m_0^*} = 0.012$ and $\frac{m_h^*}{m_0^*} = 0.28$ 8

$$n_i = 2\left(\frac{2\Pi kTm_e}{h^2}\right)^{\frac{3}{2}} e^{\frac{-E_g}{2K_b}T}$$

$$n_i = 2\left(\frac{2X3.14xXX300X9.1X10^{-31}}{6.626X10^{-34^2}}\right)^{\frac{3}{2}} (0.12X9.11X10^{-31}X0.281X9.11X10^{-31}) e^{\frac{-0.67}{2X1.38X10^{-23}}} X\left(\frac{300}{1.6X10^{-19}}\right)$$

$n_i = 4.69X10^{18}\ m^{-3}$

ii) The mobility of electrons and holes in a sample of intrinsic semiconductor Ge at 300 K are 0.36 $m^2v^{-1}s^{-1}$ and 0.17 $m^2v^{-1}s^{-1}$ respectively. Find the forbidden energy gap if the resistivity of the specimen is 2.12 Ωm. 8

$n_i = \frac{\sigma}{e(\mu_e + \mu_h)}$ and $\sigma = \frac{1}{\rho} = \frac{1}{2.12} = 0.47\ \Omega^{-1}m$

$n_i = \frac{0.47}{1.6X10^{-19}(0.36+0.17)} = 5.5\ X10^{18}\ m^{-3}$