

2. Semiconducting Materials

Part – A

1. State the properties of semiconductor?

- (i) The resistive lies between 10^{-4} to $0.5 \Omega\text{m}$
- (ii) At 0K, they behave as insulator
- (iii) The conductivity of the semiconductor increases both due to the temperature & impurity
- (iv) They have negative temperature coefficient of resistance
- (v) In semiconductors both the electron and holes are charge carriers and will take part in conduction.
- (vi) They are formed by covalent bonds

2. What are elemental and compound semiconductor? Give Example?

Elemental semiconductors (Indirect Band gap Semiconductors) are made from single element of fourth group elements of the periodic table.

Eg: Silicon, Germanium

Semiconductors (Indirect Band gap Semiconductors) which are formed by combining third and fifth group elements or second and sixth group elements of the periodic table are called compound semiconductors.

Eg: GaAs, InP, MgO, ZnS, etc.,

3. Differentiate Indirect and Direct Band gap semiconductor?

S.No	Indirect Bandgap Semiconductor	Direct Bandgap Semiconductor
1.	Heat produced during recombination	Photons emitted during recombination
2.	Life time of charge carriers is more	Life time of charge carriers is less
3.	They are used as diodes, transistors, etc.,	They are used as LED's, Laser diodes and IC's, etc.,
4.	Current amplification is more	Current amplification is less

4. What is meant by intrinsic and extrinsic semiconductor?

S.No	Intrinsic Semiconductor	Extrinsic Semiconductor
1.	It is the purest form of Semiconductor	It is due to adding Impurities to semiconductor
2.	Charge carriers are only due to thermal agitation	Charge carriers are due to impurities and thermal agitation
3.	They have low electrical conductivity	They have high electrical conductivity
4.	They have low operating temperature	They have low operating temperature
5.	At 0K, Fermi energy lies between	At 0K, Fermi energy is close to

	valence band & conduction band	conduction band in 'n' type semiconductor & close to valence band in 'p' type semiconductor
--	--------------------------------	---

5. Define Fermi level in semiconductors? Mention its position in intrinsic & Extrinsic Semiconductor?

Fermi level is the energy level which separates the filled and empty energy states

Intrinsic Semiconductor: Here the Fermi level exactly lies between lowest energy level of conduction band and highest energy level of valence band $E_f = \frac{E_c + E_v}{2}$

'N-type Semiconductor' the Fermi energy lies exactly between minimum energy level of conduction band and donor energy level $E_f = \frac{E_c + E_d}{2}$

'P-type Semiconductor' the Fermi energy lies exactly between the acceptor energy level and the maximum energy level of valence band $E_f = \frac{E_c + E_a}{2}$

6. Define Hall Effect and Hall Voltage?

When a conductor carrying a current (I) is placed in a transverse magnetic field (B), a potential difference (Electric field) is produced inside the conductor in a direction normal to the direction of both the current and magnetic field. This phenomenon is known as **Hall Effect** and the generated voltage is called **Hall voltage**

7. State the law of mass action in semiconductor?

The product of electron & hole concentration remains constant at a given temperature and is equal to the square of intrinsic carrier concentration i.e., $n_i.n_e = n_i^2$

8. What are the applications of Hall Effect?

- (i) It is used to determine whether the material is p-type or n- type semiconductor
- (ii) It is used to find carrier concentration
- (iii) It is used to determine the sign of the current carrying charges
- (iv) It is used to measure magnetic flux density using a semiconductor sample of known hall coefficient.

9. Mention any four advantages of semiconducting materials?

- (i) It can behave as insulators at 0K and as conductors at high temperature
- (ii) They possess crystalline structure

- (iii) N-type & p-type semiconductors are prepared by adding impurities with the charge carriers of electrons and holes respectively.
- (iv) They find applications in manufacturing Diodes, Transistors, IC's , etc.,

10. Write an expression for carrier concentration in intrinsic semiconductor?

$$\text{Intrinsic carrier concentration } n_i = 2 \left[\frac{2\pi kT}{h^2} \right]^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} e^{\left[\frac{-E_g}{2kT} \right]}$$

Where m_e^* - Effective mass of electron; m_h^* - Effective mass of hole; E_g - Band gap

11. Write an expression for carrier concentration in n - type semiconductor?

$$\text{Carrier concentration of n - type semiconductor is } n_i = [2N_d]^{1/2} \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{4}} e^{\left[\frac{E_d - E_c}{2kT} \right]}$$

Where m_e^* - Effective mass of electron; N_d - donor concentration; E_d - donor energy level;

E_c - Energy level in conduction band

12. Write an expression for carrier concentration in p - type semiconductor?

$$\text{Carrier concentration of p - type semiconductor is } n_i = [2N_a]^{1/2} \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{4}} e^{\left[\frac{E_v - E_a}{2kT} \right]}$$

Where m_e^* - Effective mass of electron; N_a - acceptor concentration; E_a - acceptor energy level; E_v - Energy level in valence band.

13. Define donors and acceptors and state its ionization energy?

Donors are the penta valent atoms which donates electrons to the pure semiconductors. The energy required to donate an electron from donor energy level to the conduction band by $\Delta E = E_c - E_d$ is called ionization energy of donor

Acceptors are the trivalent atoms which accept electrons from the pure semiconductor. The energy required to move an electron from valence band to acceptor energy level by $\Delta E = E_a - E_v$ is called ionization energy of acceptor.

Part – B

1. Derive an expression for the intrinsic carrier concentration of a semiconductor?

The number of charge carriers per unit volume of the material is called carrier concentration or density of charge carriers

Electrons in Conduction Band

The number of electrons whose energy lies in the range “E” & “E+dE” in the conduction band is given by $dn = Z(E) F(E) dE$ (1)

Where $Z(E)$ – density of states in the energy ranges ‘E’ & ‘E + dE’

$F(E)$ – Probability of number of electron occupying in the conduction band

The number of electrons in the conduction band for the entire region is calculated by integrating equation (1) from top energy level ‘ E_c ’ to bottom energy level ‘ α ’

$$\text{i.e., } n = \int_{E_c}^{\infty} Z(E)F(E)dE \quad (2)$$

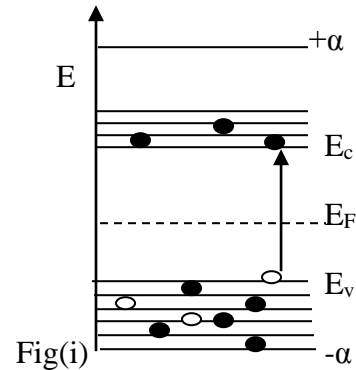
W.K.T, Density of states in the conduction band in the energy range ‘E’ & ‘E+dE’ is given by $Z(E) dE = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} E^{\frac{1}{2}} dE$ (3)

The bottom edge of the conduction band (E_c)

represents the potential energy of an electron at rest. Therefore,

$(E - E_c)$ is the kinetic energy of the conduction electron at higher

energy levels. Therefore the equation (3) is modified as



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

Since the electron is moving in a periodic potential, its mass m is replaced by its effective mass m_e^* .

The probability of electron occupancy is given by $F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$ (5)

Substituting (4) & (5) in (2), we get, $n = \int_{E_c}^{\infty} \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} \times \frac{1}{1 + e^{(E-E_F)/kT}} dE$ (6)

For all possible temperature, $E - E_F \gg kT$, hence in the denominator, $1 + e^{\frac{E-E_F}{kT}} \cong e^{\frac{E-E_F}{kT}}$

Now equation (6) becomes, $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_c}^{\infty} \frac{(E - E_c)^{\frac{1}{2}}}{e^{(E-E_F)/kT}} dE$

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

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

To solve this, assume the following:

$E - E_c = x$	$E = E_c$	$E = +\alpha$
$E = E_c + x$	$E_c - E_c = x$	$\alpha - E_c = x$
$dE = dx$	$x = 0$	$x = \alpha$

$$Now, \quad n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{E_F/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-(E_c + x)/kT} dx$$

$$(or) \quad n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{(E_F - E_c)/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx \quad (8)$$

$$Using \text{ gamma function, } \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx = \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2} \quad (9)$$

$$\text{Substituting eqn (9) in (8), we get, } n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{(E_F - E_c)/kT} \times \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$$

$$(or) \quad n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_F - E_c)/kT} \quad (10)$$

This is the expression of electrons in the conduction band of an intrinsic semiconductor.

Concentration of holes in the Valence band

We know that if an electron is transferred from valence band to conduction band, a hole is created in valence band. Let dp be the number of holes in the valence band for the energy range E & $E+dE$. $\therefore dp = Z(E) (1 - F(E)) dE$ (1)

Where $Z(E)$ – Density of states in the energy range E & $E+dE$

$(1 - F(E))$ – Probability of unoccupied (vacant) electron state (presence of hole) in valence band

$$\therefore (1 - F(E)) dE = 1 - \frac{1}{1 + e^{(E - E_F)/kT}} = \frac{1 + e^{(E - E_F)/kT} - 1}{1 + e^{(E - E_F)/kT}} = \frac{e^{(E - E_F)/kT}}{1 + e^{(E - E_F)/kT}} \quad (2)$$

$\because E < E_F$ in valence band, $(E - E_F)$ has negative quantity & hence in denominator $e^{(E-E_F)/kT}$ is very small when compared with 1, hence $1 + e^{(E-E_F)/kT} \cong 1$

$$\therefore 1 - F(E) = e^{(E-E_F)/kT} \quad (3)$$

E_V is the top level in the valence band and having potential energy of a hole at rest. Hence

$(E_V - E)$ is the kinetic energy of the hole at level below E_V . Hence,

$$\text{Density of states in the valence band is } Z(E)dE = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} dE \quad (4)$$

Where, m_h^* - effective mass of the hole in the valence band

$$\text{Substituting equation (4), (3) in (1), we get, } dp = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} e^{(E-E_F)/kT} dE \quad (5)$$

The number of holes in the valence band for the entire energy range is obtained by integrating

Above equation between the limits $-\alpha$ to E_V

$$\text{i.e., } \int dp = \int_{-\infty}^{E_V} \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} e^{(E-E_F)/kT} dE$$

$$\text{(or) } dp = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{-E_F/kT} \int_{-\infty}^{E_V} (E_V - E)^{\frac{1}{2}} e^{E/kT} dE \quad (6)$$

To solve this, assume the following:

$E_V - E = x$	$E = -\alpha$	$E = E_V$
$E = E_V - x$	$E_V - (-\alpha) = x$	$E_V - E_V = x$
$dE = -dx$	$x = \alpha$	$x = 0$

$$p = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{-E_F/kT} \int_{\infty}^0 x^{\frac{1}{2}} e^{-(x+E_V)/kT} (-dx)$$

$$\text{(or) } p = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{(E_V-E_F)/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx \quad (7)$$

$$\text{Using gamma function, } \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx = \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2} \quad (8)$$

Substituting eqn (8) in (7), we get, $p = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{(E_v - E_f)/kT} \times \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$

$$(or) \quad p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_v - E_f)/kT} \quad (9)$$

This is the expression of holes in the valence band of an intrinsic semiconductor

Intrinsic Carrier Concentration:

In intrinsic semiconductor, carrier concentration of electrons in conduction band (n_i) = carrier concentration of holes in valence band n_p &

hence the intrinsic carrier concentration is $n_i^2 = n_i \times n_p$

$$n_i^2 = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_f - E_c)/kT} \times 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_v - E_f)/kT} \quad (1)$$

$$(or) \quad n_i^2 = 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* \times m_h^*)^{\frac{3}{2}} e^{(E_v - E_c)/kT}$$

$$(or) \quad n_i^2 = 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* \times m_h^*)^{\frac{3}{2}} e^{-E_g/kT} \quad (2)$$

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

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

2. Discuss the variation of Fermi Level with temperature in an intrinsic semiconductor?

We know that, for an intrinsic semiconductor, the density of electron in the conduction band is equal to the density of holes in the valence band.

$$i.e., \quad n_i = n_p \quad (1)$$

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

Rearranging, we get, $e^{(E_F - E_C)/kT} = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{(E_v - E_F)/kT}$

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

Taking log on both sides, we get

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

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

(or) $E_F = \frac{kT}{2} \left[\frac{3}{2} \log_e \left(\frac{m_h^*}{m_e^*}\right) + \frac{E_v + E_c}{kT} \right] = \frac{3kT}{4} \log_e \left(\frac{m_h^*}{m_e^*}\right) + \frac{kT}{2} \left[\frac{E_v + E_c}{kT} \right]$

(or) $E_F = \frac{3kT}{4} \log_e \left(\frac{m_h^*}{m_e^*}\right) + \left[\frac{E_v + E_c}{2} \right]$ (2)

If $m_e^* = m_h^*$, then $\log_e \left(\frac{m_h^*}{m_e^*}\right) = \log_e 1 = 0$,

hence the above equation becomes, $E_F = \left[\frac{E_v + E_c}{2} \right]$ (3)

Thus, the Fermi level is located half way between the top of the valence band and bottom of the conduction band. Its position is independent of temperature. If $m_e^* < m_h^*$, thus, the Fermi level is just above the middle of energy gap and its rises slightly with increasing temperature.

3. Discuss the carrier concentration, the variation of Fermi level with temperature in the case of n –type semiconductors for low doping level?

In n –type semiconductor, the donor level is just below the conduction band. N_d denotes the donor concentration & E_d represents the energy of the donor level.

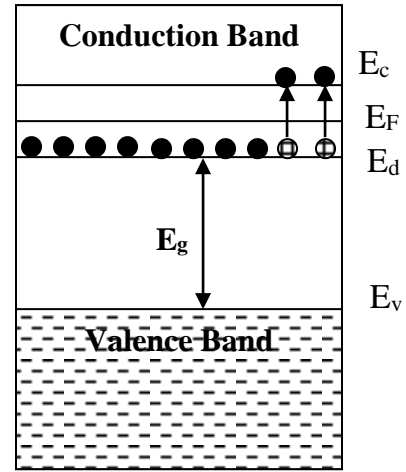
Density of electrons per unit volume in the conduction band is given by

$$n = 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_F - E_c)/kT} \quad (1)$$

here E_f – Fermi energy; E_c – Energy corresponding to the bottom of the conduction band

Density of the ionized donors = $N_d [1 - F(E)]$

$$\begin{aligned}
 &= N_d \left[1 - \frac{1}{1 + e^{(E_d - E_f)/kT}} \right] \\
 &= N_d \left[\frac{1 + e^{(E_d - E_f)/kT} - 1}{1 + e^{(E_d - E_f)/kT}} \right] \\
 &= N_d \left[\frac{e^{(E_d - E_f)/kT}}{1 + e^{(E_d - E_f)/kT}} \right]
 \end{aligned}$$



$$\text{Density of ionized donors} = \frac{\left[\frac{N_d}{1 + e^{(E_d - E_f)/kT}} \right]}{\frac{e^{(E_d - E_f)/kT}}{1 + e^{(E_d - E_f)/kT}}} = \left[\frac{N_d}{1 + e^{(E_f - E_d)/kT}} \right] \quad (2)$$

At equilibrium, the density of electrons in conduction band = Density of ionized donors.

$$\text{Equating (1) \& (2), } 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_f - E_c)/kT} = \frac{N_d}{1 + e^{(E_f - E_d)/kT}} \quad (3)$$

E_f lies more than few kT above donor levels, hence $e^{(E_d - E_f)/kT}$ is large compared to '1'. Hence the '1' in denominator of R.H.S of equation (3) is neglected.

$$2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_f - E_c)/kT} = \frac{N_d}{e^{(E_f - E_d)/kT}}$$

$$\text{(or) } 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_f - E_c)/kT} = N_d e^{(E_d - E_f)/kT} \quad (4)$$

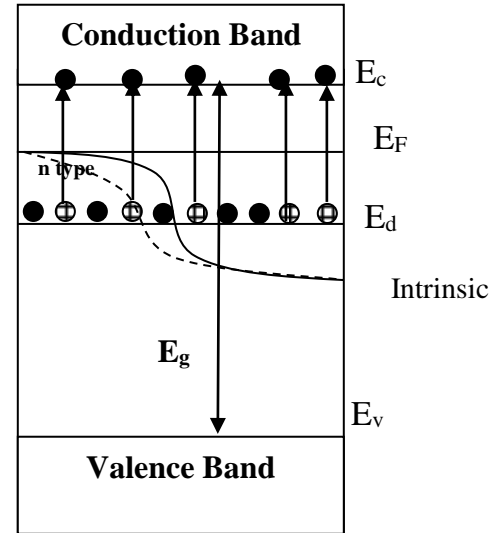
Taking log on both sides,

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

$$(or) \log \left[2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} \right] + \frac{E_F - E_c}{kT} = \log N_d + \frac{E_d - E_F}{kT} \quad (5)$$

$$(or) \frac{E_F - E_c - E_d + E_F}{kT} = \log N_d - \log \left[2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} \right]$$

$$(or) \frac{2E_F - E_c - E_d}{kT} = \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]$$



$$(or) 2E_F = E_d + E_c + kT \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]$$

$$(or) E_F = \frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right] \quad (6)$$

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

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} \exp \left[\frac{\left(\frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]} - E_c \right)}{kT} \right] \quad (7)$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} \exp \left[\frac{E_d + E_c - 2E_c + \frac{1}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]}{kT} \right]$$

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

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} \frac{\left[\frac{N_d}{2} \right]^{1/2}}{\left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/4}} e^{(E_d - E_c)/2kT} \quad (8)$$

Rearranging the expression (8), we have

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

$$(or) \quad n = (2N_d)^{1/2} \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/4} e^{(-\Delta E)/2kT}$$

Where $\Delta E = E_c - E_d$ is the ionization energy to transfer Energy from donor energy level to the conduction band.

Results:

- (i) The density of electrons is proportional to square root of donor concentration and valid at low temperature alone
- (ii) At high temperature, intrinsic carrier concentration must take along with this concentration

Variation of Fermi level with temperature and impurity concentration

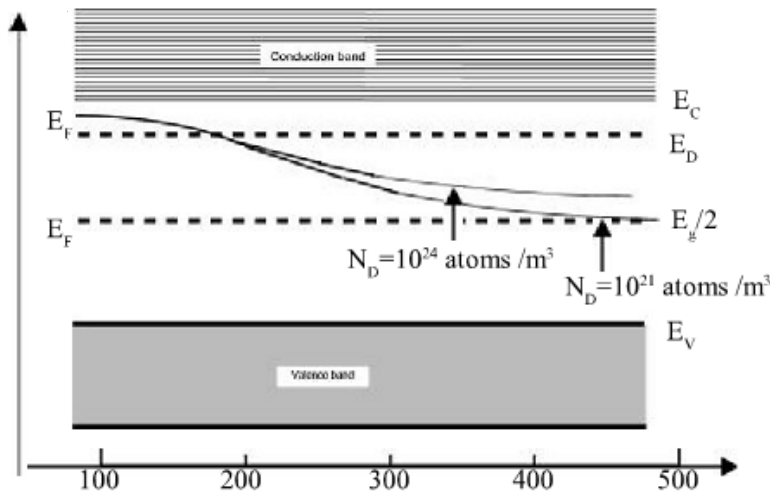
Fermi level of n - type semiconductor is

$$E_F = \frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}} \right] \quad (1)$$

At $T = 0K$, the above equation reduces to $E_F = \frac{E_d + E_c}{2}$ (2)

- (i) At $0K$, Fermi level lies exactly at the centre of the donor level and bottom of the conduction band.
- (ii) As the temperature is gradually increased from a low temperature, the contribution of electron increases and at very high temperature, it far exceeds the donor concentration and the intrinsic behaviour predominates at higher temperature.

- (iii) Fermi level shifts downwards when the temperature is increased and finally reaches the middle of the band gap (or) intrinsic Fermi level.
- (iv) Further when the concentration of donors increases, the extrinsic behaviour also extends up to very high temperature & Fermi level reaches the middle of the band gap only at high temperature.



4. Discuss the carrier concentration, the variation of Fermi level with temperature in the case of p –type semiconductors for low doping level?

In p – type semiconductor, the acceptor energy level is just above the valence band. Let E_a represents the energy of the acceptor level and N_a represents the number of acceptor atoms per unit volume.

Density of holes per unit volume in valence band is given by $p = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_v - E_F)/kT}$ (1)

Where E_v is the energy corresponding to the top of the conduction band

Density of the ionized acceptors = $N_a F(E_a) = \frac{N_a}{1 + e^{(E_a - E_F)/kT}}$ (2)

Since $E_a - E_F$ is very large when compared to kT . $e^{(E_a - E_F)/kT}$ is a large quantity and thus '1' in denominator of R.H.S of equation(2) is neglected. hence, equation(2), reduces to

$N_a F(E_a) = \frac{N_a}{e^{(E_a - E_F)/kT}} = N_a e^{(E_F - E_a)/kT}$ (3)

At equilibrium, the density of holes in Valence band = Density of ionized acceptors

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

Taking log on both sides,

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

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

Rearranging the expression (5), we have

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

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

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

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

Sub. The expression of E_F in equation (6), we get

$$p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} \exp \left[\frac{\left(E_v - \frac{E_v - E_a}{2} + \frac{kT}{2} \log \left[\frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}} \right]}{kT} \right)}{kT} \right] \quad (7)$$

$$(or) \quad p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} \exp \left[\left(\frac{2E_v - E_v - E_a}{2kT} + \frac{1}{2} \log \left[\frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}} \right] \right) \right] \quad (8)$$

$$(or) \quad p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} \frac{\left[\frac{N_a}{2} \right]^{\frac{1}{2}}}{\left[\left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}} \right]^{\frac{1}{2}}} e^{\frac{E_v - E_a}{2kT}}$$

$$(or) \quad p = (2N_a)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4} e^{(E_v - E_a)/2kT} \quad (9)$$

If $E_a - E_v = \Delta E$ is the acceptor ionization energy required to move the electron from valence band to acceptor energy level, then equation (9) becomes,

$$p = (2N_a)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4} e^{-\Delta E / 2kT} \quad (10)$$

Results:

- (i) Density of holes in valence band is proportional to square root of acceptor concentration
- (ii) At very high temperature p – type semiconductor behaves like an intrinsic semiconductor

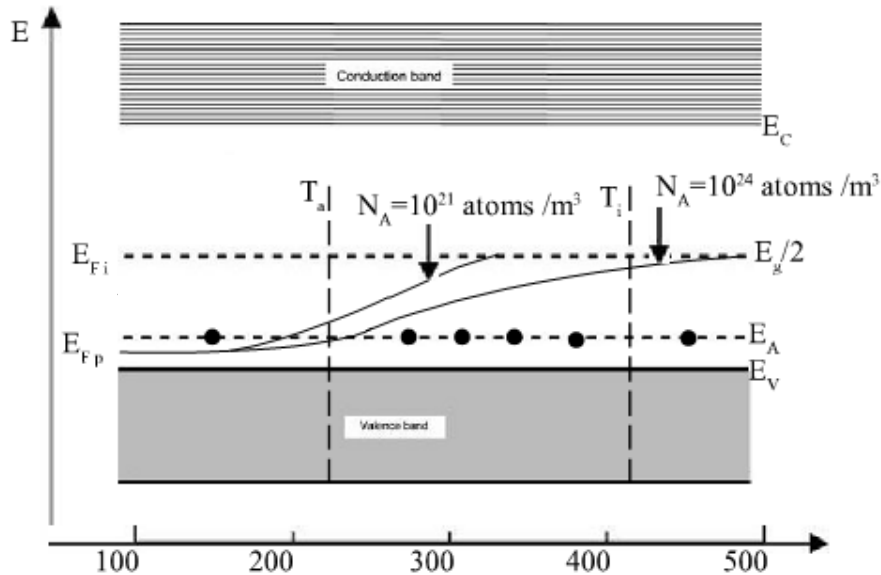
Variation of Fermi level with temperature

We know that

$$E_F = \frac{(E_a + E_v)}{2} - \frac{kT}{2} \log_e \left\{ \frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}} \right\} \quad (1)$$

At $T = 0K$, the above expression becomes, $E_F = \frac{E_a + E_v}{2}$ (2)

- (i) At $0K$ the Fermi level lies exactly halfway between acceptor level E_a and top of the valence band E_v



- (ii) As the temperature increases, the Fermi level shifts upwards, at a particular temperature, when all the acceptor atoms are ionized and Fermi level crosses the acceptor level
- (iii) At very high temperature, the Fermi level is shifted to intrinsic Fermi level and behaves as an intrinsic semiconductor

5. What is Hall Effect? Derive an expression of hall coefficient? Describe an experimental setup for the measurement of hall coefficient?

“When the conductor carrying a current (I) is placed in a perpendicular magnetic field (B), a potential difference is developed inside the conductor in a direction normal to the directions of both the current and magnetic field”

This phenomenon is known as Hall Effect and the corresponding voltage thus generated is called Hall voltage

Explanation

Consider an external field applied along the X-axis of the specimen. Assuming that the material is n -type semiconductor, the current flow consists mainly of electrons moving from right to left, corresponding to the conventional current direction.

When this specimen is placed in a magnetic field ‘ B ’ and if ‘ v ’ is the velocity of the electrons perpendicular to the magnetic field then each one of them will experience a downward force of magnitude Bev

This downward force (Lorentz Force F_L) due to magnetic field causes the electrons to be deflected in the downward direction and hence there is an accumulation of negative charges on

the bottom face of the slab. This causes the bottom face of the slab to be more negative with respect to the top face and a potential difference is established from top to bottom of the specimen. This potential difference causes a field E_H called Hall field in negative y direction. There is a force eE_H acting on the electron in the upward direction due to this field.

Theory of Hall Effect

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

$$Bev = eE_H \quad (1)$$

In a uniform sample, the electric current density (J) is related to the drift velocity as

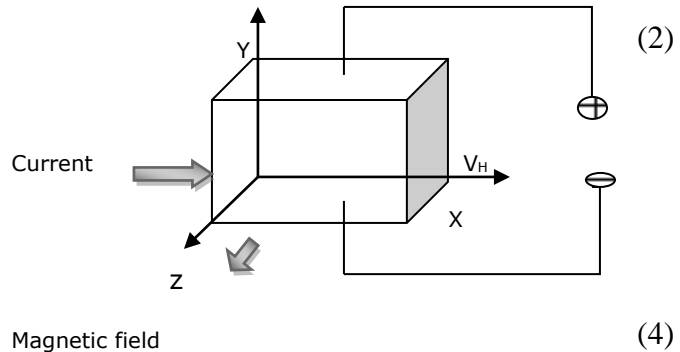
$$J = -neV$$

Where n is the concentration of electrons.

$$V = \frac{-J}{ne} \quad (2)$$

Substituting equation (2) in (1),

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



This can be written as $E_H = BJR_H$

Magnetic field

(4)

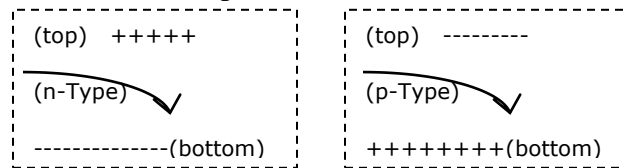
Where $R_H = -1 / ne$ is called Hall coefficient

The negative sign indicates that the developed field is in the negative y direction.

Similarly, the Hall coefficient for p -type semiconductor is $R_H = 1 / pe$.

Where p is the concentration of holes

Determination of Hall coefficient



The hall field per unit current density per unit magnetic induction is defined as hall coefficient.

If t is the thickness of the sample and V_H is the hall voltage, then $V_H = E_H t$ (5)

Where E_H is hall field.

From equation (4), we get $E_H = R_H J_x B$

Substituting the value of (5) in above equation, we get $V_H = R_H J_x B t$ (6)

Now the current density J_x can be written as $J_x = \frac{I_x}{bt}$ (7)

Where ' b ' is the width and bt is the area of cross section of the sample

Substituting equation (7) in equation (6), we get $V_H = \frac{R_H I_x B t}{bt}$

$$V_H = \frac{R_H I_x B}{b} \quad (8)$$

$$(or) \quad R_H = \frac{V_H b}{I_x B} \quad (9)$$

$$\text{For an } n\text{-type semiconductor } R_H = \frac{-V_H b}{I_x B} \quad (10)$$

Mobility of charge carriers

We know that hall coefficient $R_H = \frac{-1}{ne}$

This expression is correct only when the charge carriers is free from any attractive force in energy band and moves with constant drift velocity. But this is not true in the case of semiconductors.

Considering the average speed, it is shown that $R_H = \frac{-1.18}{ne}$ for electrons and $R_H = \frac{1.18}{pe}$ for holes.

We know that the electrical conductivity and mobility is related by $\sigma = n e \mu_e$

$$(or) \quad \mu_e = \frac{\sigma}{ne} \quad \& \quad \text{hence } \mu_e = \frac{\sigma_e}{ne} \quad \text{and hence } \mu_e = \frac{-R_H \sigma_e}{1.18} \quad (11)$$

$$\text{Similarly } \mu_h = \frac{-R_H \sigma_h}{1.18} \quad (12)$$

Experimental Determination of Hall Coefficient:

The experimental setup for the measurement of Hall voltage is shown in figure.

A semiconducting material is taken in the form of a rectangular slab of thickness 't' and breadth 'b'. A suitable current I_x ampere is allowed to pass through this sample along the X axis by connecting it to battery

The sample is placed between the poles pieces of an electromagnet such that the applied magnetic field coincides with the z – axis.

Hall voltage (V_H) which is developed in the sample is measured by fixing two probes at the centers of the bottom and top faces of the sample.

By measuring Hall voltage, Hall coefficient is calculated from the formula $R_H = \frac{-V_H b}{I_x B}$

Applications

- (i) The sign of the hall coefficient is used to determine whether a give semiconductor is n – type or p – type
- (ii) Once Hall coefficient R_H is measured, the carrier concentration can be determined from

$$n = 1/e R_H$$

- (iii) The mobility of charge carriers can be obtained if conductivity is known. $\mu_e = \sigma_e R_H$
- (iv) Hall voltage V_H for a given current is proportional to B . Hence measurement of V_H measures the magnetic field B .
- (v) This instrument gives an output proportional to the product of two signals. Thus if current I is made proportional to one input and if B is made proportional to the other input, then the Hall voltage V_H is proportional to the product of the two inputs.

