UNIT – V SEMICONDUCTING MATERIALS AND DEVICES

PART – A Questions

1. What is semiconductor?

A semiconductor is a solid which has the resistivity in between conductors and insulators. It acts as an insulator at absolute zero and as a conductor at high temperature.

2. State the properties of a semiconductor.

(i) The resistivity of a semiconductor lies between 10^{-4} to 0.5 ohm-meter.
(ii) At zero Kelvin, they behave as insulators.
(iii) At high temperature, they behave as conductors.
(iv) The conductivity of a semiconductor increases both due to the temperature and impurities.
(v) They have negative temperature coefficient of resistance.
(vi) In semiconductors, both the electrons and holes will take part in conduction.

3. Define the term 'hole' in semiconductor.

When the temperature of a semiconductor is increased, the electrons in the valence band jump into conduction band. Due to this, a (vacant site) empty space is created in valence band. This vacant site is called hole. The absence of electron is called hole. It acts as a positive charge. So, it attracts the electrons.

4. What happens when the temperature increases in the case of semiconductor and conductor?

In semiconductor, when the temperature increases, its conductivity increases.

$$\rho \propto \frac{1}{T}$$

In conductors, when the temperature increases, conductivity decreases.

$$\rho \propto T$$

5. Semiconductors have negative temperature coefficient of resistance – Give the reason.

When the temperature is increased, large numbers of charge carriers are produced due to breaking of covalent bonds. Hence these electrons move freely and give rise to conductivity.

6. What are elemental semiconductors? Give two examples.

The semiconductors made up of single element are called elemental semiconductor. They are formed by IV column elements in periodic table.

Examples: Germanium, Silicon.

7. What are compound semiconductors? Give two examples.

The semiconductors made up of more than one element (compounds) are called compound semiconductors. They are formed by combining III and V group elements or II and VI group elements in periodic table.

Examples: GaA, GaP, MgO & CdS.

8. Give differences between Elemental and Compound semiconductors. (or) Give differences between indirect band gap and direct band gap semiconductors.

Elemental semiconductors	Compound semiconductors
1. They are made up of single element. **E.g.** Ge, Si etc.	1. They are made up of (more than one element) compounds. **E.g.** GaA, GaP, MgO & CdS.
2. They are formed by IV column elements in periodic table.	2. They are formed by combining III and V group elements or II and VI group elements in periodic table.
3. They are called indirect band gap semiconductors.	3. They are called direct band gap semiconductors.
4. Heat is produced during recombination.	4. Photons are emitted during recombination.
5. Life time of charge carriers is more.	5. Life time of charge carriers is less.
6. Current amplification is more.	6. Current amplification is less.
7. They are used to manufacture of diodes and transistors.	7. They are used to manufacture of LEDs and ICs.

9. What is intrinsic semiconductor? Give some examples.

Semiconductor in a pure form is called intrinsic semiconductor.
Examples: Silicon & Germanium

10. What is extrinsic semiconductor? Give some examples.

Semiconductor which is doped with impurity is called extrinsic semiconductor.

Examples: Si doped with Al, In, P, As etc.

11. Differentiate Intrinsic and Extrinsic semiconductors.

Intrinsic semiconductor	Extrinsic semiconductor
1. Semiconductor in a pure form is called intrinsic semiconductor.	1. Semiconductor which is doped with impurity is called extrinsic semiconductor.
2. Here charge carriers are produced only due to thermal agitation.	2. Here charge carriers are produced due to impurities and may also produced due to thermal agitation.
3. They have low electrical conductivity.	3. They have high electrical conductivity.
4. They have low operating temperature.	4. They have high operating temperature.
5. At 0K, the Fermi level exactly lies between conduction band and valence band.	5. At 0K, Fermi level lies closer to conduction band in n-type and lies near to valence band in p-type semiconductors.
6. **Examples:** Si & Ge.	6. **Examples:** Si doped with Al, In, P, As etc.

12. Define carrier concentration in intrinsic semiconductor.

The number of charge carriers (electrons & holes) per unit volume of a semiconducting material is called carrier concentration.

13. Define density of electrons.

The number of electrons in the conduction band per unit volume of a semiconducting material is called electron concentration (or) density of electrons (or) number of electrons.

14. Define density of holes.

The number of holes in the valence band per unit volume of a semiconducting material is called hole concentration (or) density of holes (or) number of holes

15. Given an extrinsic semiconductor, how will you find whether it is n-type or p-type? (or) How can you distinguish p-type and n-type semiconductors using Hall Effect?

If the Hall coefficient is negative, then we ensure that the material is an *n*-type semiconductor.

If the Hall coefficient is positive, then we ensure that the material is an p-type semiconductor.

16. What is n-type semiconductor? Give some examples.

When a small amount of pentavalent impurity is added to a pure semiconductor, it is known as *n*-type semiconductor.

Examples: Intrinsic semiconductor doped with phosphorus, arsenic, antimony.

17. What is p-type semiconductor? Give some examples.

When a small amount of trivalent impurity is added to a pure semiconductor, it is known as *n*-type semiconductor.

Examples: Intrinsic semiconductor doped with boron, gallium, indium.

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

***n*-type semiconductors**	***p*-type semiconductors**
1. When a small amount of pentavalent impurity is added to a pure semiconductor, it is known as *n*-type semiconductor.	1. When a small amount of trivalent impurity is added to a pure semiconductor, it is known as *p*-type semiconductor.
2. The impurity is called donor because it donates electron.	2. The impurity is called acceptor because it accepts electron.
3. Electrons are the majority carriers.	3. Holes are majority carriers.
4. Holes are the minority carriers.	4. Electrons are the minority carriers.
5. The donor energy level is very close to the conduction band.	5. The acceptor energy level is very close to the valence band.
6. When temperature is increased, these semiconductors can easily donate an electron from donor energy level to the conduction band.	6. When temperature is increased, these semiconductors can easily donate an electron from valence band to acceptor energy level.

19. State Hall Effect.

When a conductor or a semiconductor carrying a current is placed in a perpendicular magnetic field, an electric field is produced inside the conductor. The direction of the electric field is perpendicular to both current and magnetic field. This effect is called Hall Effect and the produced voltage is called Hall voltage.

20. Mention the uses of Hall Effect. (or) What are the applications of Hall Effect?

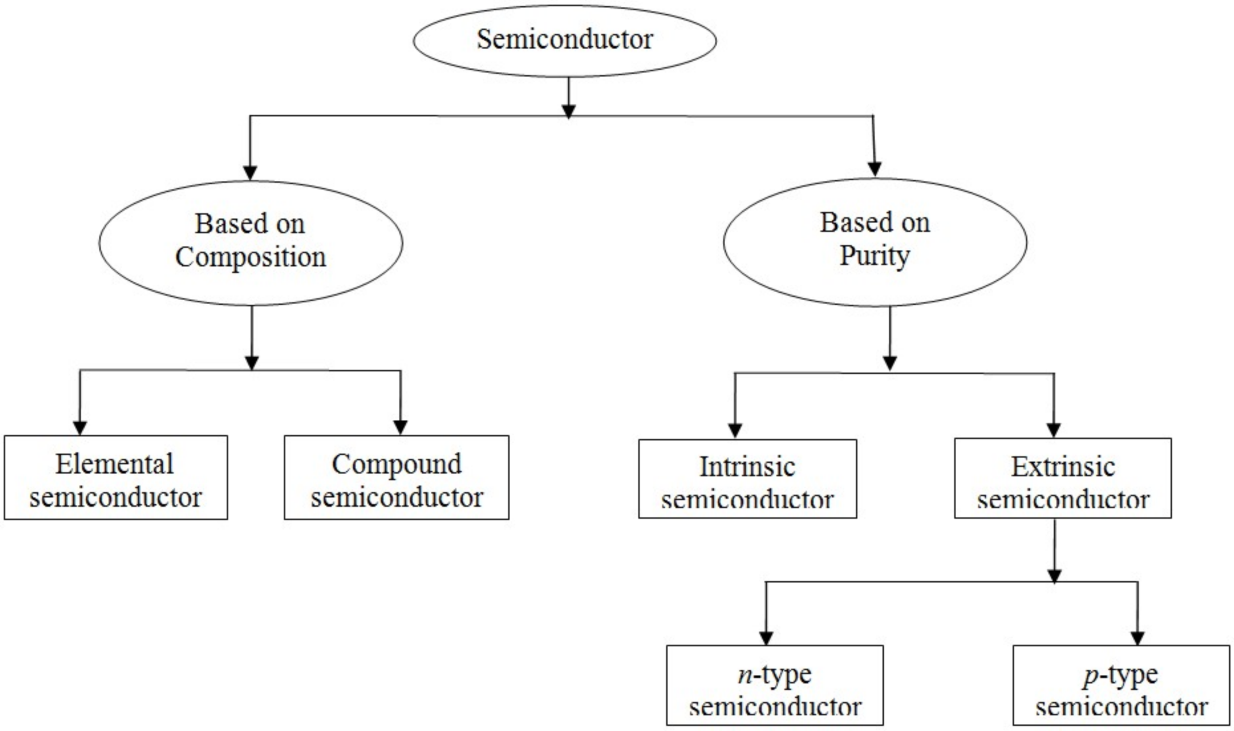
(i) It is used to determine whether the semiconductor is *p*-type or *n*-type.
(ii) It is used to find the carrier concentration.
(iii) It is used to find the mobility of charge carriers.
(iv) It is used to determine the sign of the charge carriers.
(v) It is used to design magnetic flux meters on the basis of Hall voltage.
(vi) It is used to find the power flow in an electromagnetic wave.

PART – B Important Questions

1. Explain with neat sketch the different types of semiconductors. (or) Explain with neat sketch the intrinsic and extrinsic semiconductors.

Semiconductor

A semiconductor is a solid which has the resistivity in between conductors and insulators. It acts as an insulator at absolute zero and as a conductor at high temperature.



Elemental semiconductor

(i) The semiconductors made up of single element are called elemental semiconductor. They are formed by IV column elements in periodic table.
(ii) They are called as indirect band gap semiconductors.
(iii) Here electron – hole recombination takes place through traps.
(iv) In this process, phonons are emitted.
(v) Life time of charge carriers is more due to indirect recombination.
(vi) Current amplification is more.
(vii) They are used for making diodes and resistors.
(viii) **Examples:** Germanium (Ge) & Silicon (Si).

Compound semiconductor

(i) The semiconductors made up of more than one element (compounds) are called compound semiconductors. They are formed by combining III and V group elements or II and VI group elements in periodic table.
(ii) They are called as direct band gap semiconductors.
(iii) Here electron – hole recombination takes place directly.
(iv) In this process, photons are emitted.
(v) Life time of charge carriers is less due to indirect recombination.
(vi) Current amplification is less.
(vii) They are used for making LEDs, Laser diodes and ICs.
(viii) **Examples:** GaA & MgO.

Intrinsic semiconductor

(i) A semiconductor in a pure form is called intrinsic semiconductor.
(ii) Here the charge carriers are produced only due to thermal agitation.
(iii) They have low electrical conductivity.
(iv) They have low operating temperature.
(v) At *0* K, the Fermi level exactly lies between conduction band and valence band.
(vi) **Examples:** Germanium (Ge) & Silicon (Si).

Extrinsic semiconductor

(i) Semiconductor which is doped with impurity is called extrinsic semiconductor.
(ii) Here the charge carriers are produced due to impurities and may also be produced due to thermal agitation.
(iii) They have high electrical conductivity.
(iv) They have high operating temperature.
(v) At *0* K, Fermi level lies closer to conduction band in *n*-type semiconductor and lies near valence band in *p*-type semiconductor.
(vi) **Examples:** Si and Ge doped with Al, In, P, As etc.

***n*-type semiconductor**

(i) When a small amount of pentavalent impurity is added to a pure semiconductor, it is known as *n*-type semiconductor.
(ii) Here electrons are majority carriers and holes are minority carriers.
(iii) It has donor energy levels very close to conduction bad.
(iv) When temperature is increased, these semiconductors can easily donate an electron to the conduction band.

***p*-type semiconductor**

(i) When a small amount of trivalent impurity is added to a pure semiconductor, it is known as *p*-type semiconductor.
(ii) Here holes are majority carriers and electrons are minority carriers.
(iii) It has acceptor energy levels very close to valence bad.
(iv) When temperature is increased, these semiconductors can easily accept an electron from the valence band.

2. What is Hall Effect? Derive an expression for Hall coefficient. Describe an experimental set up for the measurement of the same.

(or)

Derive an expression for the charge density in terms of Hall voltage.

(or)

What is Hall Effect? Give the theory of Hall Effect.

(or)

(i) Explain the phenomenon of Hall Effect. Obtain an expression for Hall coefficient.

(ii) How will you measure Hall coefficient experimentally?

(or)

(i) Explain Hall Effect in *n*-type and *p*-type semiconductor. Also state how Hall voltage is related.

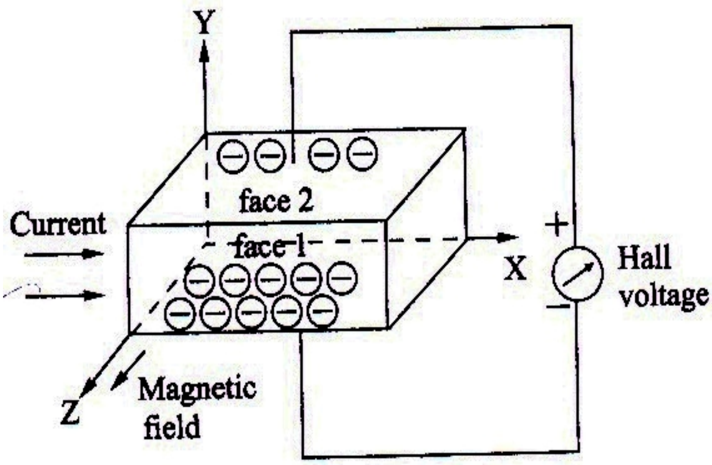
(ii) Derive an expression for Hall coefficient.

(iii) Describe the experimental set up for the measurement of Hall coefficient. (or) Describe an experiment to find the concentration of charge carrier in N-type semiconductor.

<u>Hall Effect</u>

When a conductor or a semiconductor carrying a current is placed in a perpendicular magnetic field, an electric field is produced inside the conductor. The direction of the electric field is perpendicular to both current and magnetic field. This effect is called Hall Effect and the produced voltage is called Hall voltage.

<u>Hall coefficient for *n* – type semiconductor</u>



- Consider a n – type semiconductor.
- Current is passed along x – axis.
- Magnetic field is applied along z – axis.
- Electric field will be produced in y – axis.
- Since the direction of the current is from left to right, all the electrons will move from right to left.

- All the electrons will move with a force in downward direction (face – 1) due to magnetic field.

E_H – Hall electric field
I_x – Current along x – axis
B_z – Magnetic field along y – axis
v – Velocity of electrons
e – Charge of electrons
n_e – Number of electrons in n – type semiconductor

Force due to electric field $= -eE_H$

Force due to magnetic field $= -B_z e v_x$

At equilibrium,

$$\cancel{-}\cancel{e}E_H = \cancel{-}B_z \cancel{e} v_x$$

$$E_H = B_z\, v_x$$

$$v_x = \frac{E_H}{B_z} \qquad \text{---------- (1)}$$

According to current density definition,

$$J_x = -n_e e v_x \qquad \text{---------- (2)}$$

Sub. (1) in (2)

$$J_x = \frac{-n_e e E_H}{B_z}$$

$$E_H = J_x B_z \left(-\frac{1}{n_e e}\right)$$

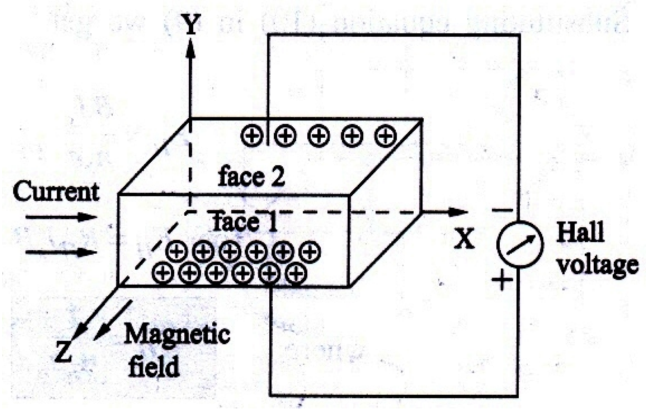
$$E_H = J_x B_z\, R_H$$

where $$R_H = \left(-\frac{1}{n_e e}\right) \qquad \text{---------- (3)}$$

$$R_H - Hall\ coefficient$$

(3) is the expression for Hall coefficient of *n* – type semiconductor.

<u>Hall coefficient for *p* – type semiconductor</u>



- Consider a p – type semiconductor.
- Current is passed along x – axis.
- Magnetic field is applied along z – axis.
- Electric field will be produced in y – axis.
- Since the direction of the current is from left to right, all the holes will move from left to right.

- All the holes will move with a force in downward direction (face – 1) due to magnetic field.

E_H – Hall electric field
I_x – Current along x – axis
B_z – Magnetic field along y – axis
v – Velocity of holes
e – Charge of holes
n_e – Number of holes in p – type semiconductor

Force due to electric field $= eE_H$

Force due to magnetic field $= B_z e v_x$

At equilibrium,

$$\cancel{e}E_H = B_z \cancel{e}v_x$$

$$E_H = B_z\, v_x$$

$$v_x = \frac{E_H}{B_z} \qquad \text{---------- (4)}$$

According to current density definition,

$$J_x = n_h e v_x \qquad \text{---------- (5)}$$

Sub. (1) in (2)

$$J_x = \frac{n_h e E_H}{B_z}$$

$$E_H = J_x B_z \left(\frac{1}{n_h e}\right)$$

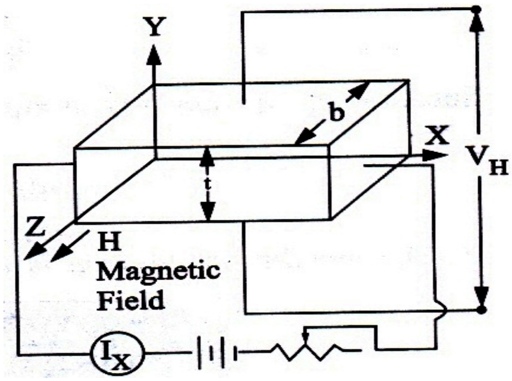
$$E_H = J_x B_z R_H$$

where $$R_H = \left(\frac{1}{n_h e}\right) \qquad \text{---------- (6)}$$

$$R_H - Hall\ coefficient$$

(6) is the expression for Hall coefficient of *p* – type semiconductor.

3. With neat diagram, describe the experimental measurement of Hall Effect.



(i) A semiconductor is taken in the form of rectangular form.
(ii) Let its thickness be 't' and breadth be 'b'.
(iii) Current (I_x) is passed along x – axis using a battery.
(iv) The semiconductor is placed between the north and south poles of an electromagnet.
(v) The magnetic field is passed z – axis.
(vi) Due to Hall Effect, Hall voltage (V_H) is developed in the semiconductor.
(vii) This voltage is measured by fixing two probes at the centers of the top and bottom faces of the semiconductor.
(viii) Then, Hall coefficient is determined by the formula $R_H = \frac{V_H b}{I_x B}$.

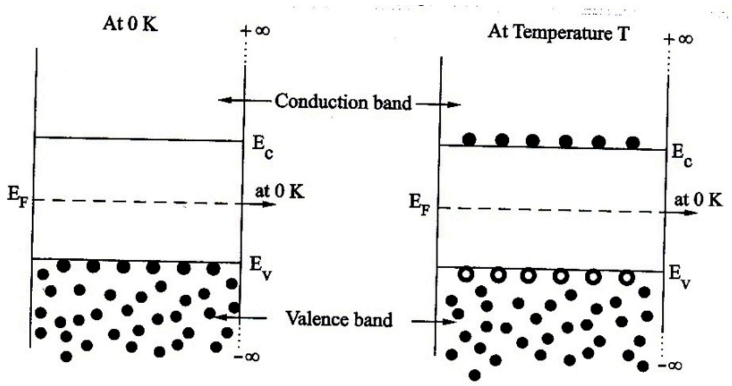
4. Derive an expression for the density of electrons (or) carrier concentration of electrons in intrinsic semiconductors.

(or)

Assume Fermi Dirac distribution function, derive an expression for the number of electrons/unit volume in the conduction band of an intrinsic semiconductor.

- The number of electrons in the conduction band per unit volume of the material is called density of electrons or electron concentration (n_e).
- At zero Kelvin, all the electrons are present in valence band.

- At high temperature, electrons cross the band gap and occupy conduction band.



The number of electrons per unit volume in conduction band

$$n_e = Z(E)\,F(E)\,dE$$

For entire region, $$n_e = \int_{E_C}^{\infty} Z(E)\,F(E)\,dE \qquad ---------- (1)$$

We know that, $$Z(E)\,dE = \frac{\pi}{2}\left[\frac{8m_e^*}{h^2}\right]^{3/2}(E-E_C)^{1/2}\,dE \qquad ---------- (2)$$

$$m_e^* \rightarrow Effective\ \ mass\ \ of\ \ electrons$$

From Fermi distribution function,

$$F(E) = \frac{1}{1+e^{(E-E_F)/K_BT}} \qquad ---------- (3)$$

Sub. (2) & (3) in (1)

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

$$n_e = \frac{\pi}{2}\left[\frac{8m_e^*}{h^2}\right]^{3/2} \int_{E_C}^{\infty} \frac{(E-E_C)^{1/2}}{1+e^{(E-E_F)/K_BT}}\,dE \qquad ---------- (4)$$

$$e^{(E-E_F)/K_BT} >>> 1$$

$$1+e^{(E-E_F)/K_BT} \approx e^{(E-E_F)/K_BT}$$

(5) becomes

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

$$n_e = \frac{\pi}{2}\left[\frac{8\,m_e^*}{h^2}\right]^{3/2}\int_{E_C}^{\infty}(E-E_C)^{1/2}\; e^{(E_F-E)/K_BT}\,dE \qquad \text{----------} (5)$$

Assume $E - E_C = x\,K_BT$ ---------- (6)

$E = E_C + x\,K_BT$ ---------- (7)

$dE = 0 + K_BT\;dx$ ---------- (8)

Sub. $E = E_C$ in (6)

$E_C - E_C = x\,K_BT$

$0 = x\,K_BT$

$\frac{0}{K_BT} = x$

$0 = x$

$x = 0$

Sub. $E = \infty$ in (6)

$\infty - E_C = x\,K_BT$

$\infty = x\,K_BT$

$\frac{\infty}{K_BT} = x$

$\infty = x$

$x = \infty$

Limit $x = (0, \infty)$

Sub. (6), (7) & (8) in (5)

$$n_e = \frac{\pi}{2}\left[\frac{8\,m_e^*}{h^2}\right]^{3/2}\int_0^{\infty}(x\,K_BT)^{1/2}\; e^{(E_F-E_C-xK_BT)/K_BT}\;(xK_BT)\,dx$$

$$n_e = \frac{\pi}{2}\left[\frac{8\,m_e^*}{h^2}\right]^{3/2}\int_0^{\infty}x^{1/2}\,(K_BT)^{3/2}\; e^{(E_F-E_C)/K_BT}\; e^{(-xK_BT)/K_BT}\,dx$$

$$n_e = \frac{\pi}{2}\left[\frac{8\,m_e^*\,K_B\,T}{h^2}\right]^{3/2} e^{(E_F-E_C)/K_BT}\int_0^{\infty}x^{1/2}\;\; e^{-x}dx$$

$$n_e = \frac{\pi}{2}\left[\frac{8\,m_e^*\,K_B\,T}{h^2}\right]^{3/2} e^{(E_F-E_C)/K_BT}\;\frac{\pi^{1/2}}{2}$$

$$\left[\because \int_0^{\infty}x^{1/2}\;\; e^{-x}dx = \frac{\pi^{1/2}}{2}\right]$$

$$n_e = \frac{1}{2}\left[\frac{8\pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T} \frac{1}{2}$$

$$n_e = \frac{1 \times 8^{3/2}}{2 \times 2}\left[\frac{\pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T}$$

$$n_e = \frac{4^{3/2} \times 2^{3/2}}{4}\left[\frac{\pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T}$$

$$n_e = \frac{\cancel{4} \times 4^{1/2}}{\cancel{4}}\left[\frac{2\pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T}$$

$$n_e = 2\left[\frac{2\pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T} \quad ---------- (9)$$

(9) is the expression for density of electrons in conduction band.

5. Derive an expression for the density of holes (or) carrier concentration of holes in intrinsic semiconductors.

(or)

Assume Fermi Dirac distribution function, derive an expression for the number of holes/unit volume in the valence band of an intrinsic semiconductor.

- The number of holes in the valence band per unit volume of the material is called density of holes or hole concentration (n_h).
- Probability of filled state = F (E)
- Maximum probability = 1
- Probability of unfilled state = 1 – F (E)

The number of holes per unit volume in valence band

$$n_h = Z(E)\,[1 - F(E)]dE$$

For entire region,

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

We know that,

$$Z(E)\,dE = \frac{\pi}{2}\left[\frac{8 m_h^*}{h^2}\right]^{3/2} (E_V - E)^{1/2}\,dE \quad ---------- (2)$$

$$m_h^* \rightarrow Effective\ \ mass\ \ of\ \ holes$$

From Fermi distribution function,

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

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

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

$$1 - F(E) = \frac{e^{(E-E_F)/K_BT}}{1 + e^{(E-E_F)/K_BT}} \qquad \text{----------} \quad (3)$$

$$e^{(E-E_F)/K_BT} <<< 1$$

$$1 + e^{(E-E_F)/K_BT} \approx 1$$

(3) becomes

$$1 - F(E) = e^{(E-E_F)/K_BT} \qquad \text{----------} \quad (4)$$

Sub. (2) & (4) in (1)

$$n_h = \int_{-\infty}^{E_V} \frac{\pi}{2} \left[\frac{8\, m_h^*}{h^2}\right]^{3/2} (E_V - E)^{1/2}\; e^{(E-E_F)/K_BT}\, dE$$

$$n_h = \frac{\pi}{2} \left[\frac{8\, m_h^*}{h^2}\right]^{3/2} \int_{-\infty}^{E_V} (E_V - E)^{1/2}\; e^{(E-E_F)/K_BT}\, dE \qquad \text{----------} \quad (5)$$

Assume $\quad E_V - E = x\, K_B T \qquad$ ---------- (6)

$E_V - x\, K_B T = E \Rightarrow E = E_V - x\, K_B T \qquad$ ---------- (7)

$dE = 0 - K_B T\; dx \qquad$ ---------- (8)

Sub. $E = -\infty$ in (6)

$E - (-\infty) = x\, K_B T$

Sub. $E = E_V$ in (6)

$E_V - E_V = x\, K_B T$

$$E+\infty = xK_BT \qquad\qquad 0 = xK_BT$$

$$\infty = xK_BT \qquad\qquad \frac{0}{K_BT} = x$$

$$\frac{\infty}{K_BT} = x \qquad\qquad 0 = x$$

$$\infty = x \qquad\qquad x = 0$$

$$x = \infty$$

$$\text{Limit } x = (\infty, 0)$$

Sub. (6), (7) & (8) in (5)

$$n_h = \frac{\pi}{2}\left[\frac{8\,m_h^*}{h^2}\right]^{3/2}\int_{\infty}^{0}(x\,K_BT)^{1/2}\; e^{(E_V - xK_BT - E_F)/K_BT}\,(-K_BT)\,dx$$

$$n_h = \frac{\pi}{2}\left[\frac{8\,m_h^*}{h^2}\right]^{3/2}\int_{0}^{\infty}x^{1/2}\,(K_BT)^{1/2}\; e^{(E_V - E_F)/K_BT}\; e^{(-xK_BT)/K_BT}\;dx$$

$$n_h = \frac{\pi}{2}\left[\frac{8\,m_h^*\,K_BT}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_BT}\int_{0}^{\infty}x^{1/2}\;e^{-x}\;dx$$

$$n_h = \frac{\pi}{2}\left[\frac{8\,m_h^*\,K_BT}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_BT}\;\frac{\pi^{1/2}}{2}$$

$$\left[\because \int_{E_C}^{\infty}x^{1/2}\;e^{-x}dx = \frac{\pi^{1/2}}{2}\right]$$

$$n_h = \frac{1}{2}\left[\frac{8\,\pi\,m_h^*\,K_BT}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_BT}\;\frac{1}{2}$$

$$n_h = \frac{1\times 8^{3/2}}{2\times 2}\left[\frac{\pi\,m_h^*\,K_BT}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_BT}$$

$$n_h = \frac{4^{3/2} \times 2^{3/2}}{4} \left[\frac{\pi m_h^* K_B T}{h^2} \right]^{3/2} e^{(E_V - E_F)/K_B T}$$

$$n_h = \frac{\cancel{4} \times 4^{1/2}}{\cancel{4}} \left[\frac{2\pi m_h^* K_B T}{h^2} \right]^{3/2} e^{(E_V - E_F)/K_B T}$$

$$n_h = 2 \left[\frac{2\pi m_h^* K_B T}{h^2} \right]^{3/2} e^{(E_V - E_F)/K_B T} \qquad \text{----------} \quad (9)$$

(9) is the expression for density of holes in valence band.

6. Derive an expression for the carrier concentration in intrinsic semiconductor.

(or)

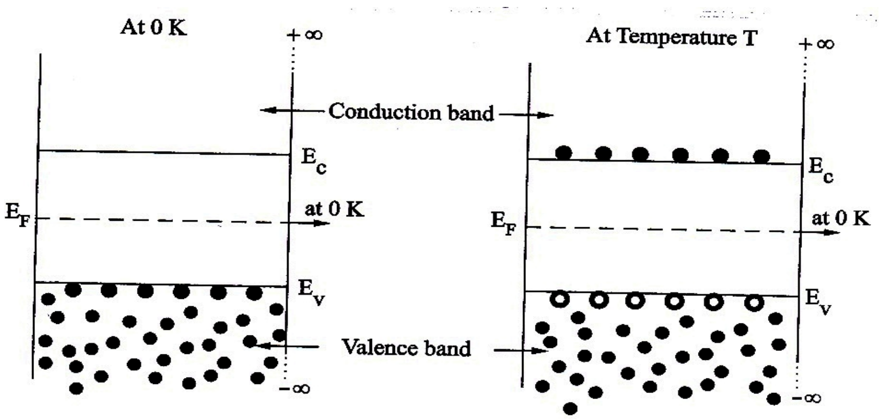
Derive the expressions for density of electrons and density of holes in intrinsic semiconductor.

<u>Carrier concentration</u>

The number of charge carriers per unit volume of the material is called intrinsic carrier concentration (n_i).

<u>Density of electrons</u>

- The number of electrons in the conduction band per unit volume of the material is called density of electrons or electron concentration (n_e).
- At zero Kelvin, all the electrons are present in valence band.
- At high temperature, electrons cross the band gap and occupy conduction band.



The number of electrons per unit volume in conduction band

$$n_e = Z(E)\, F(E)\, dE$$

For entire region, $n_e = \int_{E_C}^{\infty} Z(E)\, F(E)\, dE$ ---------- (1)

We know that, $Z(E)\, dE = \frac{\pi}{2}\left[\frac{8\, m_e^*}{h^2}\right]^{3/2} (E - E_C)^{1/2}\, dE$ ----------

(2)

$m_e^* \rightarrow Effective\ \ mass\ \ of\ \ electrons$

From Fermi distribution function,

$$F(E) = \frac{1}{1 + e^{(E-E_F)/K_B T}}$$ ---------- (3)

Sub. (2) & (3) in (1)

$$n_e = \int_{E_C}^{\infty} \frac{\pi}{2}\left[\frac{8\, m_e^*}{h^2}\right]^{3/2} \frac{(E - E_C)^{1/2}}{1 + e^{(E-E_F)/K_B T}}\, dE$$

$$n_e = \frac{\pi}{2}\left[\frac{8\, m_e^*}{h^2}\right]^{3/2} \int_{E_C}^{\infty} \frac{(E - E_C)^{1/2}}{1 + e^{(E-E_F)/K_B T}}\, dE$$ ---------- (4)

$e^{(E-E_F)/K_B T}$ >>> *1*

$$1 + e^{(E-E_F)/K_B T} \approx e^{(E-E_F)/K_B T}$$

(4) becomes

$$n_e = \frac{\pi}{2}\left[\frac{8\, m_e^*}{h^2}\right]^{3/2} \int_{E_C}^{\infty} \frac{(E - E_C)^{1/2}}{e^{(E-E_F)/K_B T}}\, dE$$

$$n_e = \frac{\pi}{2}\left[\frac{8\, m_e^*}{h^2}\right]^{3/2} \int_{E_C}^{\infty} (E - E_C)^{1/2}\, e^{(E_F - E)/K_B T}\, dE$$ ---------- (5)

Assume $E - E_C = x\, K_B T$ ---------- (6)

$E = E_C + x\, K_B T$ ---------- (7)

$dE = 0 + K_B T\ dx$ ---------- (8)

Sub. $E = E_C$ in (6)

$E_C - E_C = x\, K_B T$

$0 = x\, K_B T$

Sub. $E = \infty$ in (6)

$\infty - E_C = x\, K_B T$

$\infty = x\, K_B T$

$$\frac{0}{K_B T} = x \qquad\qquad \frac{\infty}{K_B T} = x$$

$$0 = x \qquad\qquad \infty = x$$

$$x = 0 \qquad\qquad x = \infty$$

$$\text{Limit } x = (0, \infty)$$

Sub. (6), (7) & (8) in (5)

$$n_e = \frac{\pi}{2}\left[\frac{8 m_e^*}{h^2}\right]^{3/2} \int_0^\infty (x K_B T)^{1/2} \; e^{(E_F - E_C - x K_B T)/K_B T} \; (K_B T)\, dx$$

$$n_e = \frac{\pi}{2}\left[\frac{8 m_e^*}{h^2}\right]^{3/2} \int_0^\infty x^{1/2} (K_B T)^{3/2} \; e^{(E_F - E_C)/K_B T} \; e^{(-x K_B T)/K_B T} dx$$

$$n_e = \frac{\pi}{2}\left[\frac{8 m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T} \int_0^\infty x^{1/2} \; e^{-x} dx$$

$$n_e = \frac{\pi}{2}\left[\frac{8 m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T} \frac{\pi^{1/2}}{2}$$

$$\left[\because \int_0^\infty x^{1/2} \; e^{-x} dx = \frac{\pi^{1/2}}{2}\right]$$

$$n_e = \frac{1}{2}\left[\frac{8 \pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T} \frac{1}{2}$$

$$n_e = \frac{1 \times 8^{3/2}}{2 \times 2}\left[\frac{\pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T}$$

$$n_e = \frac{4^{3/2} \times 2^{3/2}}{4}\left[\frac{\pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T}$$

$$n_e = \frac{\cancel{4} \times 4^{1/2}}{\cancel{4}}\left[\frac{2 \pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T}$$

$$n_e = 2\left[\frac{2 \pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T} \qquad \text{---------- (9)}$$

(9) is the expression for density of electrons in conduction band.

Density of holes

- The number of holes in the valence band per unit volume of the material is called density of holes or hole concentration (n_h).
- Probability of filled state = F (E)
- Maximum probability = 1
- Probability of unfilled state = 1 – F (E)

The number of holes per unit volume in valence band

$$n_h = Z(E)\,[1 - F(E)]dE$$

For entire region,

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

We know that,

$$Z(E)\,dE = \frac{\pi}{2}\left[\frac{8\,m_h^*}{h^2}\right]^{3/2} (E_V - E)^{1/2}\,dE \qquad \text{---------- (2)}$$

$$m_h^* \rightarrow Effective\ \ mass\ \ of\ \ holes$$

From Fermi distribution function,

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

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

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

$$1 - F(E) = \frac{e^{(E-E_F)/K_BT}}{1 + e^{(E-E_F)/K_BT}} \qquad \text{---------- (3)}$$

$$e^{(E-E_F)/K_BT} <<< 1$$

$$1 + e^{(E-E_F)/K_BT} \approx 1$$

(3) becomes

$$1 - F(E) = e^{(E-E_F)/K_BT} \qquad \text{---------- (4)}$$

Sub. (2) & (4) in (1)

$$n_h = \int_{-\infty}^{E_V} \frac{\pi}{2}\left[\frac{8\,m_h^*}{h^2}\right]^{3/2} (E_V - E)^{1/2}\; e^{(E-E_F)/K_BT}\,dE$$

$$n_h = \frac{\pi}{2}\left[\frac{8\,m_h^*}{h^2}\right]^{3/2} \int_{-\infty}^{E_V} (E_V - E)^{1/2}\; e^{(E-E_F)/K_BT}\, dE \qquad \text{----------}$$

(5)

Assume $\quad E_V - E = x K_B T \qquad \text{---------- (6)}$

$$E_V - x K_B T = E \Rightarrow E = E_V - x K_B T \qquad \text{---------- (7)}$$

$$dE = 0 - K_B T\; dx \qquad \text{---------- (8)}$$

Sub. $E = -\infty$ in (6)

$$E - (-\infty) = x K_B T$$

$$E + \infty = x K_B T$$

$$\infty = x K_B T$$

$$\frac{\infty}{K_B T} = x$$

$$\infty = x$$

$$x = \infty$$

Sub. $E = E_V$ in (6)

$$E_V - E_V = x K_B T$$

$$0 = x K_B T$$

$$\frac{0}{K_B T} = x$$

$$0 = x$$

$$x = 0$$

Limit $x = (\infty, 0)$

Sub. (6), (7) & (8) in (5)

$$n_h = \frac{\pi}{2}\left[\frac{8\,m_h^*}{h^2}\right]^{3/2} \int_{\infty}^{0} (x K_B T)^{1/2}\; e^{(E_V - xK_BT - E_F)/K_BT}\,(-K_B T)\, dx$$

$$n_h = \frac{\pi}{2}\left[\frac{8\,m_h^*}{h^2}\right]^{3/2} \int_{0}^{\infty} x^{1/2}\,(K_B T)^{1/2}\; e^{(E_V - E_F)/K_BT}\; e^{(-xK_BT)/K_BT}\; dx$$

$$n_h = \frac{\pi}{2}\left[\frac{8\,m_h^*\,K_B T}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_BT} \int_{0}^{\infty} x^{1/2}\; e^{-x}\; dx$$

$$n_h = \frac{\pi}{2}\left[\frac{8\,m_h^*\,K_B T}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_BT}\; \frac{\pi^{1/2}}{2}$$

$$\left[\because \int_{E_C}^{\infty} x^{1/2}\; e^{-x} dx = \frac{\pi^{1/2}}{2}\right]$$

$$n_h = \frac{1}{2}\left[\frac{8\pi m_h^* K_B T}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_B T}\ \frac{1}{2}$$

$$n_h = \frac{1\times 8^{3/2}}{2\times 2}\left[\frac{\pi m_h^* K_B T}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_B T}$$

$$n_h = \frac{4^{3/2}\times 2^{3/2}}{4}\left[\frac{\pi m_h^* K_B T}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_B T}$$

$$n_h = \frac{\cancel{4}\times 4^{1/2}}{\cancel{4}}\left[\frac{2\pi m_h^* K_B T}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_B T}$$

$$n_h = 2\left[\frac{2\pi m_h^* K_B T}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_B T} \qquad \text{----------- (9)}$$

(9) is the expression for density of holes in valence band.

<u>Intrinsic carrier concentration</u>

W.K.T. $n_i = n_e = n_h$

$$n_i^2 = n_e \,.\, n_h$$

$$n_i^2 = \left\{2\left[\frac{2\pi m_e^* K_B T}{h^2}\right]^{3/2} e^{(E_F - E_C)/K_B T}\right\}\left\{2\left[\frac{2\pi m_h^* K_B T}{h^2}\right]^{3/2} e^{(E_V - E_F)/K_B T}\right\}$$

$$n_i^2 = 4\left\{\left[\frac{2\pi K_B T}{h^2}\right]^{3/\cancel{2}}\right\}^{\cancel{2}} \left(m_e^* . m_h^*\right)^{3/2} e^{(\cancel{E_F} - E_C + E_V - \cancel{E_F})/K_B T}$$

$$n_i^2 = 4\left(\frac{2\pi K_B T}{h^2}\right)^3 \left(m_e^* . m_h^*\right)^{3/2} e^{(E_V - E_C)/K_B T} \qquad \left[\because E_C - E_V = E_g\right]$$

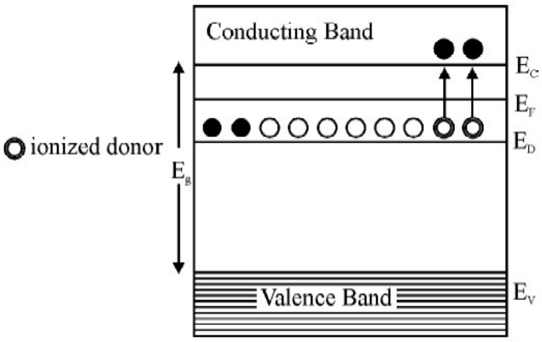
$$n_i = 2\left(\frac{2\pi K_B T}{h^2}\right)^{3/2} \left(m_e^* . m_h^*\right)^{3/4} e^{-E_g/2K_B T}$$

7. Derive an expression for carrier density in n-type semiconductor.

When a small amount of pentavalent impurity is added to a pure semiconductor, it is known as *n*-type semiconductor.

Density of electrons in conduction band in an intrinsic semiconductor is

$$N_e = \left[2\left[\frac{2\pi m_e^* K_B T}{h^2}\right]^{3/2} \exp\left[\frac{E_F - E_c}{K_B T}\right]\right] \qquad \dots (1)$$



Put $$N_c = 2\left[\frac{2\pi m_e^* K_B T}{h^2}\right]^{3/2}$$

Density of electrons

$$N_e = N_c \exp\left[\frac{E_F - E_c}{K_B T}\right] \qquad \dots (2)$$

Density of ionized donor atoms is

$$N_D[1 - F(E_D)] = N_D \exp\left[\frac{E_D - E_F}{K_B T}\right] \qquad \dots (3)$$

At equilibrium condition,

$$\begin{bmatrix} \text{Number of electrons} \\ \text{per unit volume in} \\ \text{conduction band } \textbf{(eqn (2)} \end{bmatrix} = \begin{bmatrix} \text{Number of holes} \\ \text{per unit volume in donar} \\ \text{energy level } \textbf{(eqn (3)} \end{bmatrix}$$

$$N_c \exp\left[\frac{E_F - E_C}{K_B T}\right] = N_D \exp\left[\frac{E_D - E_F}{K_B T}\right]$$

$$\frac{\exp\left[\frac{E_F - E_C}{K_B T}\right]}{\exp\left[\frac{E_D - E_F}{K_B T}\right]} = \frac{N_D}{N_c}$$

$$\exp\left[\frac{E_F - E_C - E_D + E_F}{K_B T}\right] = \frac{N_D}{N_c}$$

Taking log on both sides, we get,

$$\log\left[\exp\left[\frac{E_F - E_C - E_D + E_F}{K_B T}\right]\right] = \log\left[\frac{N_D}{N_c}\right]$$

$$\left[\frac{E_F - E_C - E_D + E_F}{K_B T}\right] = \log\left[\frac{N_D}{N_c}\right]$$

$$2E_F = (E_C + E_D) + K_B T \log\left[\frac{N_D}{N_c}\right]$$

$$E_F = \frac{(E_C + E_D)}{2} + \frac{K_B T}{2}\log\left[\frac{N_D}{N_c}\right] \quad \ldots (4)$$

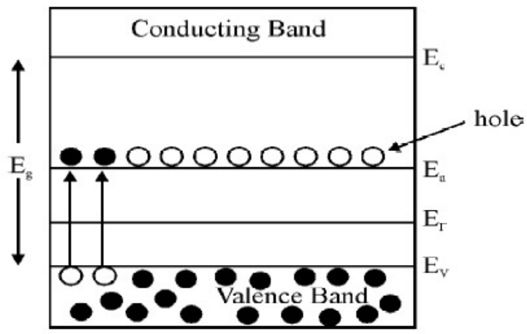
At T = 0 K. $$E_F = \left[\frac{(E_C + E_D)}{2}\right] \quad \ldots (5)$$

At T = 0 K. Thus, the Fermi level in N-type semiconductor lies exactly in middle of the conduction level (E_C) and donor level (E_D).

This equation shows that the electron concentration in the conduction band is proportional to the square root of the donor concentration.

8. Derive an expression for carrier density in p-type semiconductor.

When a small amount of trivalent impurity is added to a pure semiconductor, it is known as *p*-type semiconductor.



Density of holes in the valence band in an intrinsic semiconductors is

$$N_h = 2\left[\frac{2\pi m_h^* K_B T}{h^2}\right]^{3/2} \exp\left[\frac{E_V - E_F}{K_B T}\right] \quad \ldots (1)$$

Put
$$N_V = 2\left[\frac{2\pi m_h^* K_B T}{h^2}\right]^{3/2} \quad \ldots (2)$$

Density of holes
$$N_h = N_V \exp\left[\frac{E_V - E_F}{K_B T}\right] \quad \ldots (3)$$

Density of ionized acceptor atoms is

$$N_A F[E_A] = N_A \exp\left[\frac{E_F - E_A}{K_B T}\right] \quad \ldots (4)$$

At equilibrium condition,

$$\left[\begin{array}{c}\text{Number of holes}\\ \text{per unit volume in}\\ \text{valence band } \textbf{(eqn (3)}\end{array}\right] = \left[\begin{array}{c}\text{Number of electron}\\ \text{per unit volume in accepter}\\ \text{energy level } \textbf{(eqn (4)}\end{array}\right]$$

$$N_V \exp\left[\frac{E_V - E_F}{K_B T}\right] = N_A \exp\left[\frac{E_F - E_A}{K_B T}\right]$$

$$\exp\left[\frac{E_V - E_F}{K_B T}\right]\exp\left[\frac{-[E_F - E_A]}{K_B T}\right] = \frac{N_A}{N_V}$$

$$\exp\left[\frac{E_V - E_F - E_F + E_A}{K_B T}\right] = \frac{N_A}{N_V}$$

Taking log on both sides, we get,

$$\log\left[\exp\left[\frac{E_V - E_F - E_F + E_A}{K_B T}\right]\right] = \log\left[\frac{N_A}{N_V}\right]$$

$$\left[\frac{E_V - E_F - E_F + E_A}{K_B T}\right] = \log\left[\frac{N_A}{N_V}\right]$$

$$E_V - E_F - E_F + E_A = K_B T \log\left[\frac{N_A}{N_V}\right]$$

$$-2E_F = -[E_V + E_A] + K_B T \log\left[\frac{N_A}{N_V}\right]$$

$$E_F = \frac{(E_V + E_A)}{2} - \frac{K_B T}{2}\log\left[\frac{N_A}{N_V}\right]$$

Substituting the value N_V

$$E_F = \frac{(E_v + E_A)}{2} - \frac{K_B T}{2}\log\left[\frac{N_A}{2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/2}}\right] \quad \ldots (5)$$

At $T = 0\,K$

$$E_F = \left[\frac{(E_V + E_A)}{2}\right]$$

At 0 K fermi level in p type semiconductor lies exactly at the middle of the acceptor level and the top of the valance band.

9. Discuss carrier transport in n-type and p-type semiconductor in detail.

Carrier transport

In semiconductor, electrons and holes are called charge carriers. They move from one position to another and this movement of charge carriers is called **carrier transport**.

RANDOM MOTION of charge carriers

In the absence of electric field, the charge carriers move in random motion (in all directions).

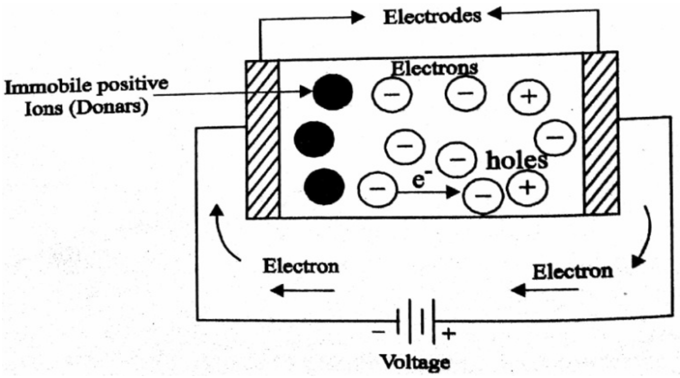
DRIFT MOTION of charge carriers

When the electric field is applied, the charge carriers move with a velocity called drift velocity and reach a steady state.

(i) Carrier transport in *n*-type semiconductor

- In n-type semiconductor, electrons are majority charge carriers.
- Holes are minority charge carriers.
- Apart from this, there will be equal number of immobile positive ions.

Diagram



Explanation

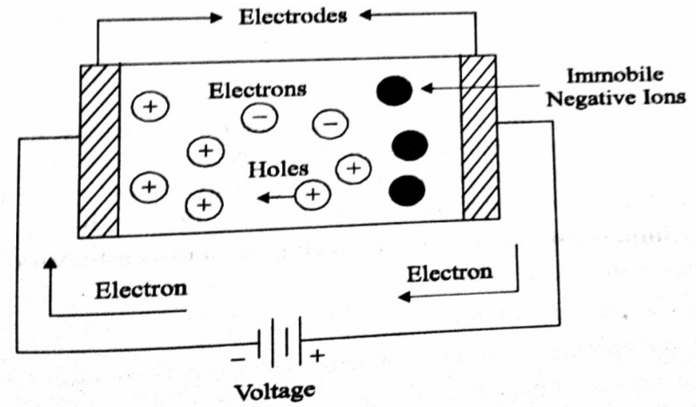
- Consider an *n*-type semiconductor.
- It is placed between a pair of electrodes.
- An Electric field (voltage) is applied to the electrodes.
- Due to applied field, the electrons move towards the positive terminal and disappear.
- At the same time, equal number of electrons is generated in the negative terminal.
- These electrons are attracted by the immobile positive ions.
- Therefore electrons flow continuously from one terminal to the other terminal.
- The net current flow depends upon the biasing voltage.

(ii) Carrier transport in p-type semiconductor

- In p-type semiconductor, holes are majority charge carriers.
- Electrons are minority charge carriers.

- Apart from this, there will be equal number of immobile negative ions.

Diagram



Explanation

- Consider a *p*-type semiconductor.
- It is placed between a pair of electrodes.
- An Electric field (voltage) is applied to the electrodes.
- Due to applied field, the holes move towards the negative terminal and disappear.
- At the same time, equal number of holes is generated in the positive terminal.
- These holes are attracted by the immobile negative ions.
- Therefore holes flow continuously from one terminal to the other terminal.
- The net current flow depends upon the biasing voltage.

10. Derive the expressions for drift transport and diffusion transport.

Drift transport

- In the absence of electric field, the charge carriers (electrons & holes) move in all directions. This is called random motion.
- In the presence of electric field, the electrons move towards the positive terminal and the holes move towards the negative terminal. The net movement of charge carriers (electrons & holes) is called drift transport.
- The current density due to electron drift is

$$J_e = n_e e v_d \qquad \text{---------- (1)}$$

- Drift velocity is directly proportional to applied electric field.

$$v_d \propto E$$

$$v_d = \mu_e E \qquad \text{----------} (2)$$

Sub. (2) in (1)

$$J_e = n_e e \mu_e E \qquad \text{----------} (3)$$

Where μ_e - mobility of electrons

- Similarly, the current density due to hole drift is

$$J_h = n_h e \mu_h E \qquad \text{----------} (4)$$

Where μ_h - mobility of holes

- Total drift current is $J = J_e + J_h$ ---------- (5)

Sub. (3) & (4) in (5)

$$J = n_e e \mu_e E + n_h e \mu_h E$$

$$J = (n_e e \mu_e + n_h e \mu_h) E \qquad \text{----------} (6)$$

According to Ohm's law,

$$J = \sigma E \qquad \text{----------} (7)$$

Compare (6) & (7)

$$\sigma \cancel{E} = (n_e e \mu_e + n_h e \mu_h) \cancel{E}$$

$$\sigma = (n_e e \mu_e + n_h e \mu_h) \qquad \text{----------} (8)$$

For intrinsic semiconductor,

$$n_e = n_h = n_i$$

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

$$\sigma_i = n_i e (\mu_e + \mu_h) \qquad \text{----------} (9)$$

<u>Diffusion transport</u>

While doping, excess charge carriers are introduced in the material. It leads to non-uniform distribution of charge carriers at some places.

When the electric field is applied, the charge carriers move from the higher concentration region to lower concentration region in order to attain uniform distribution. This transport is called **diffusion transport**.

The concentration of charge carrier (Δn_e) varies with distance (x) in a semiconductor.

$$\text{Rate of flow of charge carrier} \propto \frac{\partial}{\partial x}\Delta n_e$$

Rate of flow of electrons

$$\text{Rate of flow of electrons} \propto \frac{\partial}{\partial x}\Delta n_e$$

$$\text{Rate of flow of electrons} = -D_e \frac{\partial}{\partial x}\Delta n_e$$

D_e – Electron diffusion coefficient.

Current density due to electrons

Current density = charge of electrons x rate of flow of electrons

$$J_e = [-e]\left[-D_e \frac{\partial}{\partial x}\Delta n_e\right]$$

$$J_e = e\,D_e \frac{\partial}{\partial x}\Delta n_e \qquad \text{---------- (10)}$$

Current density due to holes

Current density = charge of holes x rate of flow of holes

$$J_h = [+e]\left[-D_h \frac{\partial}{\partial x}\left(\Delta n_h\right)\right]$$

$$J_h = -e\,D_h \frac{\partial}{\partial x}\left(\Delta n_h\right) \qquad \text{---------- (11)}$$

Drift and diffusion transport

If an electric field is applied to a semiconductor, the total current contribution is due to drift and diffusion transport.

Total current density due to electrons

$$J_e\,(Total) = J_e\,(drift) + J_e\,(diffusion)$$

$$J_e\,(Total) = n_e\, e\, \mu_e\, E + e\, D_e \frac{\partial}{\partial x}(\Delta n_e) \qquad \text{---------- (12)}$$

Similarly, total current density due to holes

$$J_e\,(Total) = n_h\, e\, \mu_h\, E - e\, D_h \frac{\partial}{\partial x}(\Delta n_h) \qquad \text{---------- (13)}$$

Total current density due to electrons and holes

$$J\,(Total) = n_e\, e\, \mu_e\, E + e\, D_e \frac{\partial}{\partial x}(\Delta n_e) + n_h\, e\, \mu_h\, E - e\, D_h \frac{\partial}{\partial x}(\Delta n_h) \qquad \text{------ (14)}$$

(14) represents the total current density due to drift and diffusion electrons and holes in semiconductors.