

Unit 4

Semiconductor Physics :-

Course objectives :-

To teach students basic concepts and principles of physics relate them to laboratory experiments and their applications.

course outcome (CO4)

Students will be able to understand theory of semiconductors and their applications in some semiconductor devices.

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Materials are classified into

- solids
- liquids
- gases

Further solids are classified into conductors, insulators and semiconductors on the basis of free electrons or valence electron.

Free electron theory :-

Electrical conduction is one of the important properties of solids.

Electrical properties → valence electrons

First time by Paul Drude, electron model was proposed. He assumed that the valence electrons become free in solids and move about randomly within the solid, as well same as molecules in a gas.

Further this electron model underwent successive modifications, which explain the electrical behaviour and the distinction between the three types of solids.

Classical free electron theory:-

Theory was proposed by Paul Drude in 1900 and later was extended by Lorentz. Therefore this theory is known as Drude-Lorentz theory.

Assumptions / Postulates of Drude - Lorentz or classical free electron theory.

- (1) The valence electrons of atoms are free to move about the whole volume of the metals like the molecules of a perfect gas in a container.
 - (2) Free electrons move in random directions. All the collisions are elastic in nature i.e. there is no loss of energy.
 - (3) Momentum of free electrons obeys the classical laws of the kinetic theory of gases.
 - (4) Electron velocities in a metal obeys the classical Maxwell - Boltzmann distribution of velocities.
 - (5) Electrons move in a completely uniform potential field due to ions fixed in the lattice.
 - (6) Free electrons are accelerated in the direction opposite to the direction of applied field.
 - (7) Mutual repulsion is negligible, so they can move in all possible directions with all the velocities.
 - (8) In absence of field, energy associated with an electron at temp. T is, $\frac{3}{2} k T$
- $\therefore \frac{3}{2} k T = \frac{1}{2} m v_{th}^2$
- $v_{th} \rightarrow$ Thermal velocity.

- (9) Electrons move in zigzag path with a small average velocity opposite to the electric field which is known as drift velocity.
- (10) The average time between two collisions is known as mean collision time and the average distance covered by the electrons between collisions is known as mean free path.
- (11) Classical theory failed to explain Compton & photoelectric effect. Success of classical free electron theory.
- 1) It explains the electrical and thermal conductivities of metals.
 - 2) It verifies Ohm's law
 - 3) Optical properties can be explained.

Limitations / Failure of classical free electron theory.

- (1) The classical free electron theory predicts the resistivity is directly proportional to square root of absolute temp. But experimentally, Resistivity is directly proportional to the absolute temp.
- (2) According to classical theory, molar specific heat at constant volume of metal (electron), $C_V = \frac{3}{2} R$. But experimentally,

3) The classical theory says, more larger conductivity for divalent and trivalent atoms (e.g. zinc, aluminium) as compared to monovalent (Cu, Ag).

But in reality, monovalent copper and silver are better conductors than zinc and aluminium.

4) According to classical theory, mean free path must be of the order of interatomic spacing in the crystal. But experimentally, mean free path is many interatomic spacings and it also depends on temp.

$$\text{mean free path} \propto \frac{1}{\text{Temp.}}$$

5) The classical theory predicts that the magnetic susceptibility of metals to be inversely proportional to temp. Experimentally, Susceptibility is independent of temp.

Some important definitions.

1) Drift Velocity :- (v_d)

Drift velocity is defined as the average velocity acquired by the free electrons of a metal in a particular direction by the application of electric field.

27 Relaxation time (τ_R)

Relaxation time is defined as the time taken by the free electrons to reach equilibrium position from the distributed position in presence of electric field.
OR

Time taken for the drift velocity to decay to $(1/e)$ of its original value.

$$v_d = v_0 e^{-t/\tau_R}$$

$v_d \rightarrow$ drift velocity of an e-

$v_0 \rightarrow$ initial velocity of an e-

$\tau_R \rightarrow$ Relaxation time

$t \rightarrow$ time

$$t = \tau_R \quad \therefore v_d = v_0 e^{-1}$$

$$\boxed{v_d = \frac{v_0}{e}}$$

Mean collision time (τ_{avg})

The average time taken by the electrons between two consecutive collisions of electrons with the lattice points is called mean collision time

$$\tau_{avg} = \frac{\lambda}{v_{th}}$$

v_{th} - thermal velocity

$\lambda \rightarrow$ ~~area~~ length mean free path

4) Current density (J)

It is defined as the magnitude of current passing through unit area

$$J = \frac{I}{A}$$

5) Mean free path: - (λ)

The average distance travelled by the electrons between two successive collisions is called a free path & their mean is called mean free path.

6) Mobility of electrons

Mobility is the measurement how easily electron moves through solid material under the influence of an electric field.

If is drift velocity per unit electric field strength.

$$\mu = \frac{V_d}{E} = \frac{e\tau}{m}$$

Thus the faster particle moves at a given electric field strength, the larger the mobility.

Energy states of an isolated atom:

- (1) The states of an electron in atom are quantum numbers, n, l, m_l , & m_s
 - (2) Principal quantum number $n = 1, 2, 3, 4, \dots$ corresponds to shells K, L, M, N, ...
 - (3) The maximum number of electrons in the shell $2n^2$
 - (4) Orbital quantum number l , from 0 to $n-1$ specifies subshells (s, p, d, f)
 - (5) magnetic quantum number m_l , from -1 to +1
 - (6) spin quantum number m_s $+\frac{1}{2}$ and $-\frac{1}{2}$
- 7) According to pauli's exclusion principle, no two electrons in atom can have the same set of quantum number, n, l, m_l, m_s

"No two electrons can exist in the same quantum states in an atom".

Quantum Theory of free electron
 According to quantum free electron theory of metals, a conduction electron in a metal experiences constant (or zero) potential and free to move inside the crystal but will not come out of

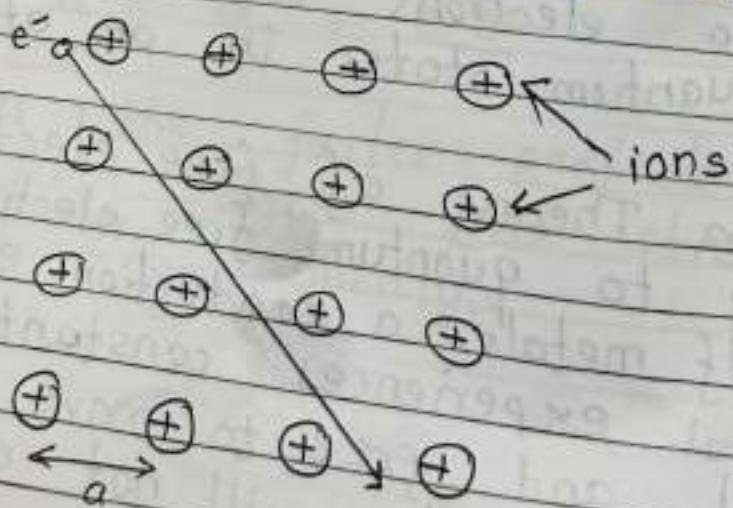
the metal because an infinite potential exists at the surface. Quantum theory successfully explains electrical conductivity, specific heat, thermionic emission and paramagnetism. Quantum theory failed to explain the difference between conductors, insulators and semiconductors and positive Hall coefficient of metals and lower conductivity of divalent α metals than that of monovalent α metals.

Opening of band gap due to internal electron diffraction.

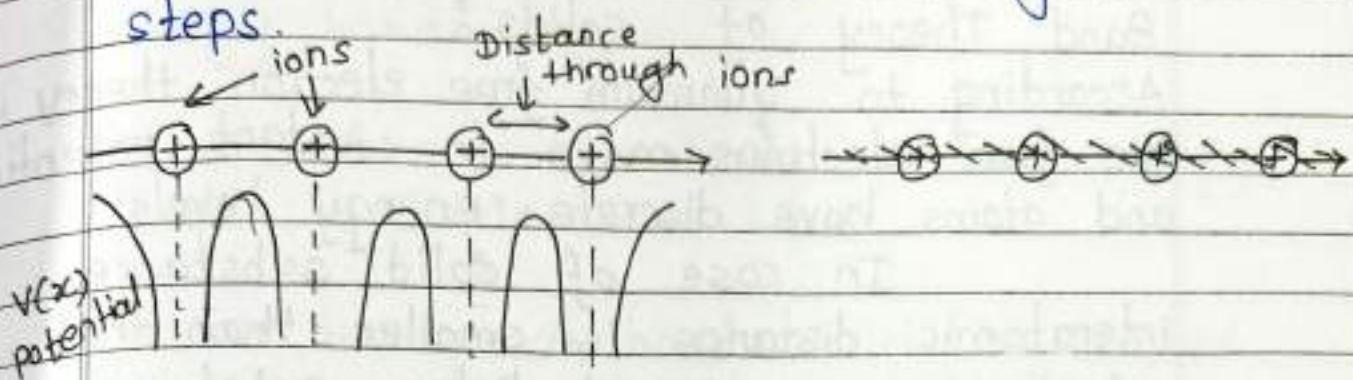
(Kronig penny model)

when an electron moves through a lattice of positive ions, it experiences varying potential.

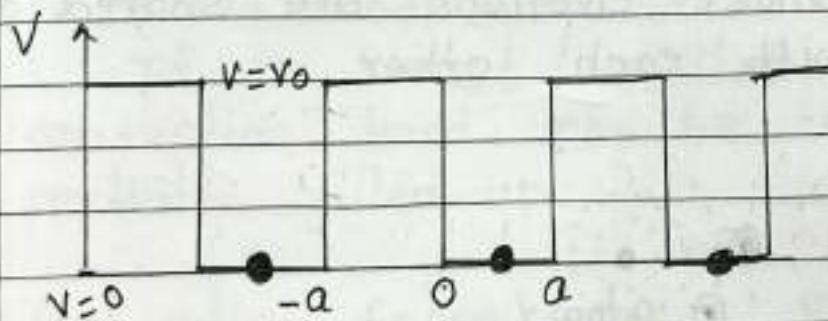
The potential of an electron at the positive ion site is zero and is maximum in between two ions.



The potential experienced by an electron, when it passes along a line through a positive ions is shown irregular steps.



It is not easy to solve Schrödinger's equation with these potentials. So, Kronig and Penny approximated these potential inside the crystal to the shape of rectangular steps. This model is called Kronig Penny Model.



The energies of electrons can be known by solving Schrödinger's wave equation in such lattice.

As electron is moving in a periodic potential, it appears that there are gaps which open in energy spectrum at an integer of ka/π . These gaps correspond to energy bands inside the solid.

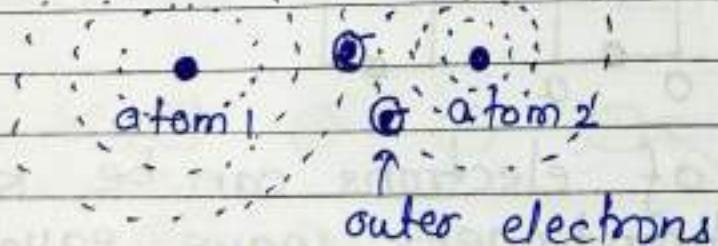
Thus the energy levels of electron in the crystal lattice is discrete.

Band Theory of solids :-

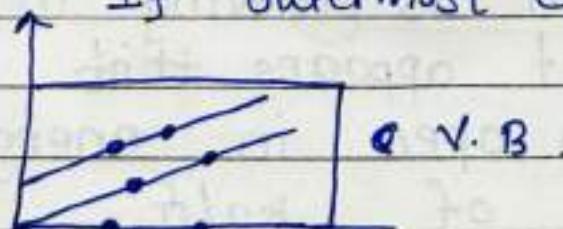
According to quantum free electron theory, the free electrons move in constant potential and atoms have discrete energy levels.

In case of solid substance interatomic distance is smaller than that of gaseous & liquid substance. Hence there is an interaction between any two successive atoms. Due to this interaction the energy levels of all atoms overlap with each other.

When two or isolated atoms are bring close to each other. Then outermost electrons are shared or interact with each other.



These outer electrons are binded with each other. If outermost electrons are more than two.



As per pauli's exclusion principle, no two electrons can occupy the same

The electrons in same orbit exhibit different energy levels. The grouping of these different energy level is called energy bands.

Band:- A set of closely packed energy levels is called as band.

valence band:- A band which is occupied by the valence electrons is called as valence band.

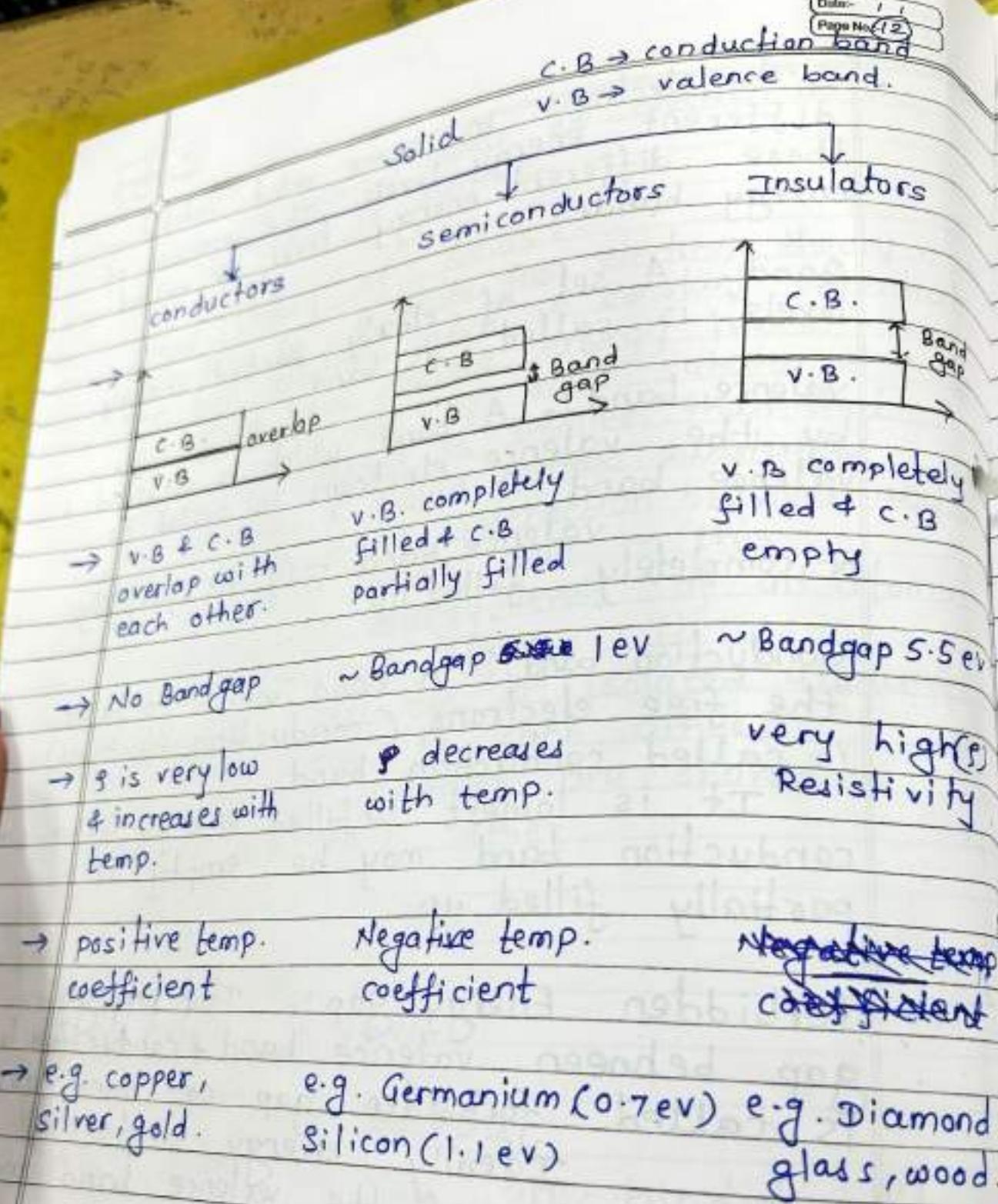
valence band may be partially or completely filled up.

Conduction band:- A band which contains the free electrons (conducting electrons) is called conduction band.

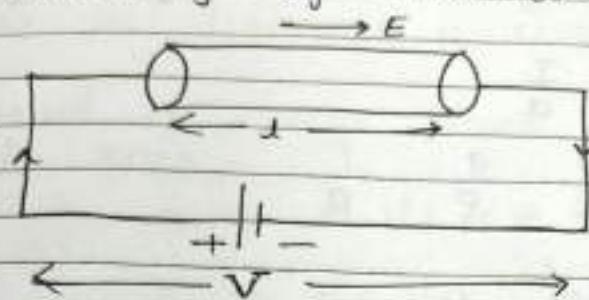
It is lowest unfilled energy band. conduction band may be empty or partially filled up.

forbidden Energy gap:- The energy gap between valence band & conduction band is called forbidden gap or band gap.

Ideally energy difference between top of the valence band and bottom of the conduction band.



Conductivity of conductors :



Consider a conductor of length l having unit cross sectional area, a .

Resistivity of the conductor is

$$\rho = \frac{Ra}{l} \rightarrow ① \quad \therefore R = \rho \frac{l}{a} \rightarrow ②$$

$\rho \rightarrow$ Resistivity

$R \rightarrow$ Resistance of conductor

$l \rightarrow$ length of conductor

$a \rightarrow$ cross-sectional area.

conductivity is reciprocal of resistivity.

$$\text{conductivity } \delta = \frac{1}{\rho} \rightarrow ③$$

By Ohm's law, $V = IR$

$$I = \frac{V}{R} \rightarrow ④$$

Substituting ① in eqn ④

$$I = \frac{V}{\left[\rho \frac{l}{a}\right]} = \frac{V}{l} \times \frac{a}{\rho} \rightarrow ⑤$$

Current density J is current flowing per area.

$$J = \frac{I}{a}$$

from ④

$$J = \frac{V}{l} \cdot \frac{q}{\rho} \cdot \frac{1}{a}$$

$$J = \frac{V}{l} \cdot \frac{1}{\rho}$$

but $\frac{V}{l} \rightarrow$ electric field E

$\frac{1}{\rho} \rightarrow$ reciprocal of resistivity \rightarrow conductivity

$$\therefore J = \sigma E \quad \rightarrow ⑤$$

Current density is defined as the amount of charge that flows through unit cross sectional area per unit time.

Let v_d be the drift velocity. Then distance travelled by electron in 1 second $= 1 \times v_d = v_d$

As electron travel distance v_d in 1 sec $a \rightarrow$ cross sectional area.

The volume of conductor is $v_d \times a$. say unit cross-sectional $a = 1$

$$\therefore \text{volume} = v_d \times 1 = v_d$$

Number of electrons that cross unit area in 1 second = $n \cdot V_d$, $n \rightarrow$ no. of e- per unit volume

Amount of charge flows through the unit area

$$= n \cdot V_d \times e$$

$$I = n e V_d \rightarrow ⑥$$

Equating ⑤ + ⑥

$$6E = n e V_d$$

$$6 = \frac{n \cdot e \cdot V_d}{E}$$

$$\boxed{6 = n \cdot e \cdot u} \quad \left(\frac{V_d}{E} = u \right)$$

current flowing through conductor is,

$$I = T \cdot a \quad \dots \quad (T = \frac{I}{a})$$

$$\boxed{I = n \cdot e \cdot a V_d} \quad \dots \quad \text{from } ⑥$$

Conductivity of the conductor semiconductor.

In a semiconductor, the current is due to free electrons as well as holes. As we know that current flowing through conductor is

$$I = n \cdot e \cdot a V_d \rightarrow ①$$

If current is due to electrons,

$$I_e = n_e \cdot e \cdot a v_e \rightarrow ②$$

$n_e \rightarrow$ number of electrons per unit area

$v_e \rightarrow$ drift velocity of electrons.

If current is due to holes,

$$I_h = n_h \cdot e \cdot a v_h \rightarrow ③$$

$n_h \rightarrow$ number density of holes

$v_h \rightarrow$ drift velocity of holes.

∴ Total current is $I = I_e + I_h$
from eqⁿ ② + ③

$$I = e \cdot a \cdot (n_e v_e + n_h v_h)$$

But current density $J = \frac{I}{a}$

$$\therefore J = e \cdot (n_e v_e + n_h v_h) \rightarrow ④$$

$$\text{but } J = \sigma E \rightarrow ⑤$$

Equating ④ + ⑤

$$\sigma E = e (n_e v_e + n_h v_h)$$

$$\sigma = e \left[n_e \cdot \frac{v_e}{E} + n_h \cdot \frac{v_h}{E} \right]$$

but $\frac{V_d}{E} = \mu \quad \therefore \frac{V_e}{E} = \mu_e \rightarrow \text{mobility of electrons}$

$\frac{V_h}{E} = \mu_h \rightarrow \text{mobility of holes.}$

$$\therefore J = e(n_e \cdot \mu_e + n_h \cdot \mu_h)$$

For Intrinsic semiconductors,

$$n_e = n_h = n_i$$

$$J = e \cdot n_i (\mu_e + \mu_h)$$

for Pn-type $n_e >> n_h$

$$J = n_e \cdot e \cdot \mu_e \quad \dots \text{electrons are majority charge carriers}$$

for p-type type

$$J = n_h \cdot e \cdot \mu_h \quad \dots \text{Holes are majority charge carriers.}$$

The current due to motion of electrons and holes in a semiconductor under the action of applied electric field is drift current.

The current which is due to density difference of charge carriers is known as diffusion current.

1) calculate the band gap energy in silicon given that it is transparent to radiation of wavelength greater than 11000 A°

→ Given data,

$$h = 6.63 \times 10^{-34} \text{ JS}$$

$$c = 3 \times 10^8 \text{ m/s}$$

$$\lambda = 11000 \text{ A}^\circ = 11000 \times 10^{-10} \text{ m}$$

$$Eg = h\nu = \frac{hc}{\lambda}$$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{11000 \times 10^{-10}}$$

$$Eg = 1.8082 \times 10^{-19} \text{ J}$$

$$= \frac{1.8082 \times 10^{-19}}{1.6 \times 10^{-19}}$$

$$Eg = 1.13 \text{ eV}$$

2) Calculate the wavelength at which germanium starts to absorbs light.

The energy gap in germanium is 0.7 eV.

→ Given data, $h = 6.63 \times 10^{-34} \text{ JS}$

$$c = 3 \times 10^8 \text{ m/s}$$

$$Eg = \frac{hc}{\lambda} \quad \therefore \lambda = \frac{hc}{Eg}$$

$$\lambda = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{0.7 \times 1.6 \times 10^{-19}} = 1.776 \times 10^{-6} \text{ m}$$

$$\lambda = 17760 \text{ A}^\circ$$

3) Calculate the conductivity of pure silicon at room temperature when the concentration of carriers is 1.6×10^{10} per cm^3 . Take $\mu_e = 1500 \text{ cm}^2/\text{V-s}$ & $\mu_h = 500 \text{ cm}^2/\text{V-s}$ at room temp.

→ Given data,

$$n_i = 1.6 \times 10^{10} \text{ per } \text{cm}^3$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

$$\mu_e = 1500 \text{ cm}^2/\text{V-s}$$

$$\mu_h = 500 \text{ cm}^2/\text{V-s}$$

$$6i = n_i \cdot e \cdot (\mu_e + \mu_h)$$

$$= 1.6 \times 10^{10} \times 1.6 \times 10^{-19} (1500 + 500)$$

$$6i = 5.12 \times 10^{-6} \text{ mho/cm}$$

(4) calculate the number of acceptors to be added to a Germanium sample to obtain the resistivity of 10^{-2} cm . $\mu = 1700 \text{ cm}^2/\text{V-s}$

→ Given data,

$$\mu = 1700 \text{ cm}^2/\text{V-s} = \mu_h$$

$$\rho = 10^{-2} \text{ cm}$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

$$\mu_h \approx 6 = n_h \cdot e \cdot \mu_h$$

$$\frac{1}{\rho} = \frac{1}{n_h \cdot e \cdot \mu_h}$$

$$n_h = \frac{1}{\rho \cdot e \cdot \mu_h}$$

$$= \frac{1}{10 \times 1.6 \times 10^{-19} \times 1700}$$

$$n_h = 3.676 \times 10^{14} \text{ per cm}^3$$

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6) Calculate small and a
2 V
Given

- 5) calculate the number of donor atoms which must be added to an intrinsic semiconductor to obtain the resistivity as $10^6 \Omega \cdot \text{cm}$, $\mu_e = 1000 \text{ cm}^2/\text{V.s}$
- Given data ,

$$\mu_e = 1000 \text{ cm}^2/\text{V.s}$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

$$\rho = 10^6 \Omega \cdot \text{cm} , n_e = ?$$

$$b = n_e \cdot e \cdot \mu_e$$

$$\rho = \frac{1}{b} = \frac{1}{n_e \cdot e \cdot \mu_e}$$

$$n_e = \frac{1}{\rho \cdot e \cdot \mu_e}$$

$$= \frac{1}{10^6 \times 1.6 \times 10^{-19} \times 1000}$$

$$n_e = 6.25 \times 10^{21} \text{ per cm}^3$$

6) Calculate the current produced in a small germanium plate of area 1 cm^2 and of thickness 0.3 mm when a P.D. of 2 V is applied across the faces.

Given data,

$$n_i = 2 \times 10^{19} \text{ /m}^3$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

$$\mu_e = 0.36 \text{ m}^2/\text{V.s}$$

$$\mu_h = 0.17 \text{ m}^2/\text{V.s}$$

$$I = ?$$

$$I = n_i \cdot e (\mu_e + \mu_h)$$

$$= 2 \times 10^{19} \times 1.6 \times 10^{-19} (0.36 + 0.17)$$

$$I = \frac{2 \times 10^{-4}}{0.3 \times 10^{-3}}$$

$$I = 1.13 \text{ A}$$

7) Calculate the conductivity of extrinsic silicon at room temperature if the donor impurity added is 1 in 10^8 silicon atoms.

Given, $n_i = 1.5 \times 10^{10}$ per cm^3

$$\mu_e = 1300 \text{ cm}^2/\text{V.s}$$

number of silicon atoms per unit volume $= 5 \times 10^{22}$.

$$I = ?$$

$$\rightarrow n_i \rightarrow 1.5 \times 10^{10} \text{ per cm}^3$$

$$n_e = 1300 \text{ cm}^2/\text{V}\cdot\text{s}$$

$$\text{Number of atoms per unit volume} = 5 \times 10^{22}$$

$$n = n_i \cdot e \cdot n_e$$

If there is 1 donor atom per 10 silicon atoms, then the number of donor atoms per cm^3

$$n_d = \frac{\text{number of silicon atoms / unit volume}}{10^8}$$

$$= \frac{5 \times 10^{22}}{10^8}$$

$$n_d = 5 \times 10^{14}$$

Assuming all the donors are ionised
 $n >> p$, hole conduction is can be neglected.

$$n_h = n \cdot e \cdot n_e$$

$$n_h = n_d \cdot e \cdot n_e$$

$$= 5 \times 10^{14} \times 1.6 \times 10^{-19} \times 1300$$

$$n_h = 0.104 \text{ mho/cm.}$$

Density of states :-

The energy band in a solid can accommodate a large number of electrons in the energy levels.

Every energy level in a energy band consist of two states and state accommodate only one electron. Thus, an electron can have only two states with opposite spin

the number of states lying in the range of energies between E & $E+dE$ is,

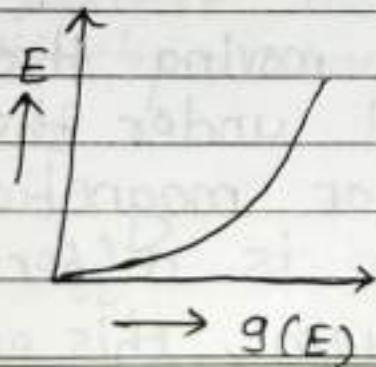
$$g(E)dE = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} \cdot dE$$

$g(E) \rightarrow$ density of states function.

$m \rightarrow$ mass of e^- , $h \rightarrow$ planck's constant.

The density of state is defined as the number of available electron states per unit volume per unit energy range at a certain energy level.

$g(E)$ is independent of the dimensions of the potential box (L)



Number of available states decreases with energy and becomes zero at the bottom edge of the band.

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We can the number of charge carriers per unit volume within a given energy range depends both on number of available states and probability that charge carrier can occupy the states.

The carrier concentration in energy range dE will be the product of the density states and probability of their occupation.

$$N(E) dE = P(E) g(E) dE$$

$N(E)$ \rightarrow carrier concentration function
 $P(E)$ \rightarrow probability function.

Effective Mass:-

We generally assume that the mass of an electron in a solid is the same as the mass of a free electron.

However, experimentally measured values indicates that in some solids the electron's mass is slightly larger or slightly smaller, than that of free electron mass. This is because of external electric or magnetic field.

The electron moving through this changing potential under the action of external electric or magnetic field, the mass of electron is different than free electron in vacuum, this experimentally

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determined electron mass is called effective mass m^*

Free electron in vacuum has well defined mass and obeys Newtonian mechanics when accelerated by an electric field.

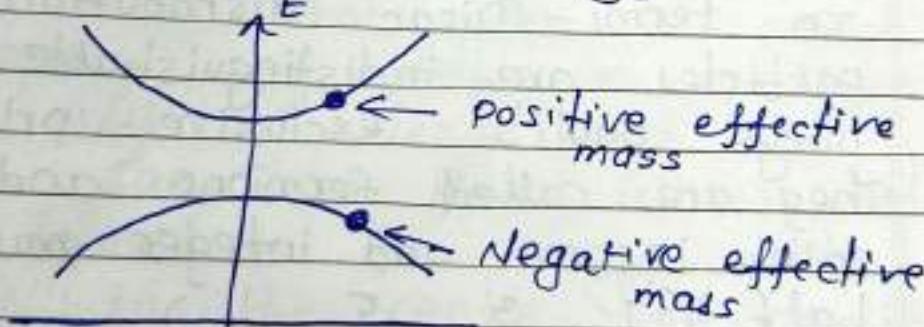
$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

$$\therefore \frac{d^2 E}{dk^2} = \frac{\hbar^2}{m}$$

for effective mass

$$\therefore m^* = \frac{\hbar^2}{\frac{d^2 E}{dk^2}}$$

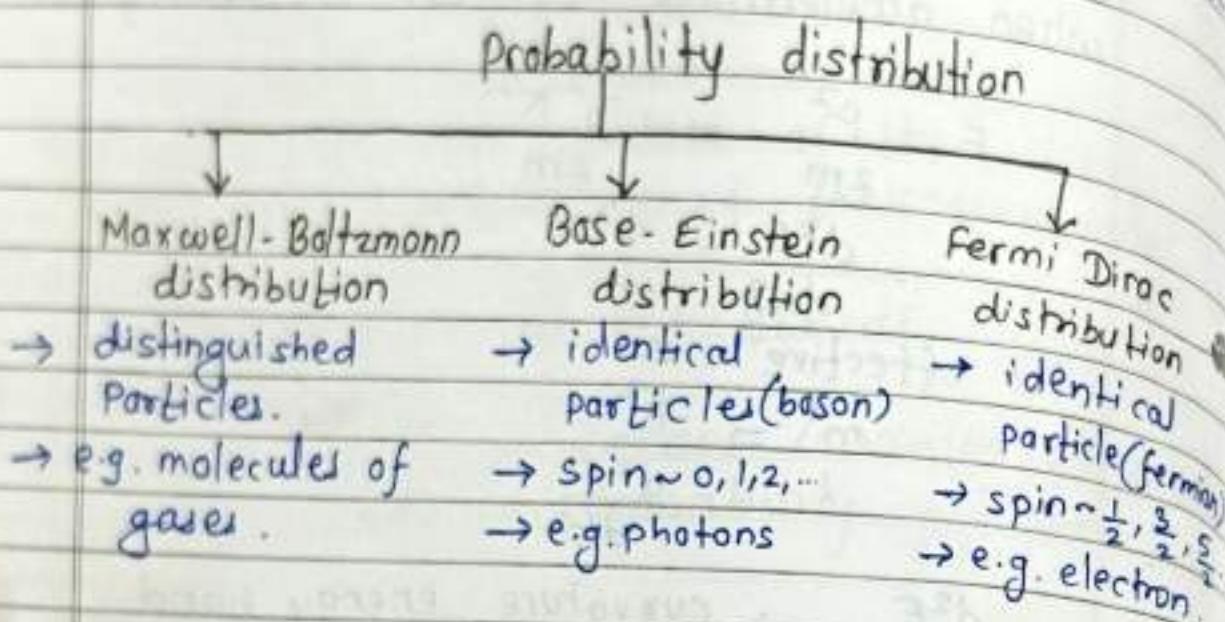
$\frac{d^2 E}{dk^2} \rightarrow$ curvature energy band



The effective mass of an electron is negative near the top of the valence band & positive near the bottom of the next conduction band.

Fermi-Dirac Probability distribution.

statistically, probabilities of occupying the available energy states are distributed in three different types.



In Fermi-Dirac distribution, all particles are indistinguishable and it obeys Pauli's exclusive principle. They are called fermions and they have spin, is an odd integer multiple of half ($\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \dots$)

The Fermi-Dirac probability distribution function or Fermi function is,

$$P(E) = \frac{1}{1 + e^{(E - E_f)/kT}}$$

$P(E)$ → probability of an electron in E

E_f → Fermi energy level.

k → Boltzmann constant

T → absolute temp.

Probability of the electron to occupy the energy level E increases with temperature.

$E_f \rightarrow$ fermi energy

Fermi level in conductors or metals:-
The highest filled state is called the fermi level and corresponding energy is called the fermi energy.

The fermi level in conductors is defined as the highest filled state in the highest energy band which contains electrons in a metal, at $0K$ is called the fermi level and its corresponding energy is called the fermi energy E_f .

Fermi Level in semiconductors:-

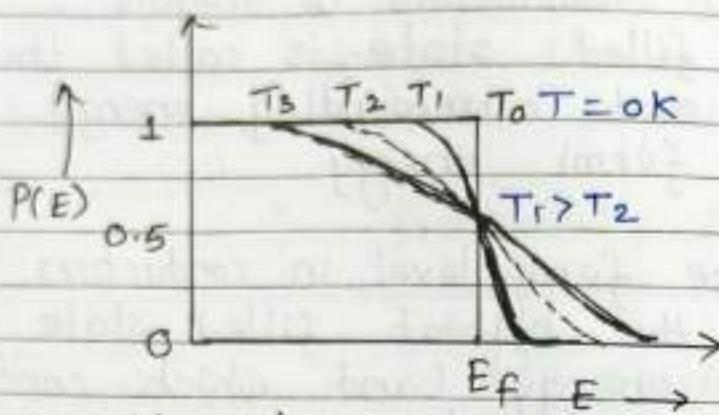
In semiconductors, the fermi level is a reference level that gives the probability of occupancy of states in conduction band as well as in valence band.

The fermi level in semiconductors can be defined as the energy which corresponds to the center of gravity of conduction electrons and holes "weighted according to their energies".

Effect of Temperature on fermi-Dirac distribution:-

According to Fermi - Dirac distribution, the probability of electron occupying an energy level $\approx E$ is,

$$P(E) = \frac{1}{1 + e^{(E-E_f)/kT}} \rightarrow ①$$



case i) At $T = 0\text{K}$ and $E < E_f$

$$P(E) = \frac{1}{1 + e^{-\infty}} \quad E - E_f = -ve$$

$$= \frac{1}{1 + 0} \quad e^{-\infty} = 0$$

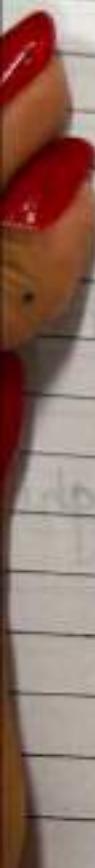
$$P(E) = 1$$

At absolute zero temp, if $E < E_f$,
the probability of finding electron
is 1.

All the energy levels below fermi
energy level are completely occupied
by electrons or are completely filled.

case ii) At $T = 0\text{K}$ and $E > E_f$

$$P(E) = \frac{1}{1 + e^{\infty}}, \quad E - E_f = +ve$$



$$P(E) = \frac{1}{1 + \infty} = \frac{1}{\infty}$$

$$P(E) = 0$$

thus at absolute zero temp. if $E > E_f$, the probability of finding the electron with the energy is greater than fermi energy is 0.

All the energy levels above fermi level are completely empty.

case iii) at $T = 0$, $E = E_f$

Here probability of occupancy can not be determined.

case iv) At $T > 0K$, $E = E_f$

$$P(E) = \frac{1}{e^0 + 1} = \frac{1}{1+1} = \frac{1}{2}$$

Hence at $T > 0K$ & $E_f = E$, prob. = $1/2$
There is equal probability of that the energy levels above and below fermi energy level are occupied by electrons.

Position of fermi level in intrinsic semiconductor:-

The fermi - Dirac probability function is,

$$P(E) = \frac{1}{1 + e^{(E-E_f)/kT}} \rightarrow ①$$

At $0K$, the solid is like an insulator
i.e. no conduction is possible as valence band is completely filled and conduction band is completely empty.

At $T > 0K$

say $n_c \rightarrow$ number of e^- in the conduction band
 $n_v \rightarrow$ number of e^- in the valence band

$$N = n_c + n_v = \text{number of } e^- \text{ in both} \\ \rightarrow \textcircled{2} \text{ the bands.}$$

According to probability theory

$$P(E_c) = \frac{n_c}{N}$$

$$n_c = N \cdot P(E_c) \rightarrow \textcircled{3}$$

$$n_c = N \cdot \frac{1}{1 + e^{(E_c - E_f)/kT}} \rightarrow \textcircled{4}$$

& similarly

$$n_v = N \cdot \frac{1}{1 + e^{(E_v - E_f)/kT}} \rightarrow \textcircled{5}$$

from eqⁿ \textcircled{2}

$$N = \frac{N}{1 + e^{(E_c - E_f)/kT}} + \frac{N}{1 + e^{(E_v - E_f)/kT}}$$

$$I = \frac{1}{1 + e^{(E_c - E_f)/kT}} + \frac{1}{1 + e^{(E_v - E_f)/kT}}$$

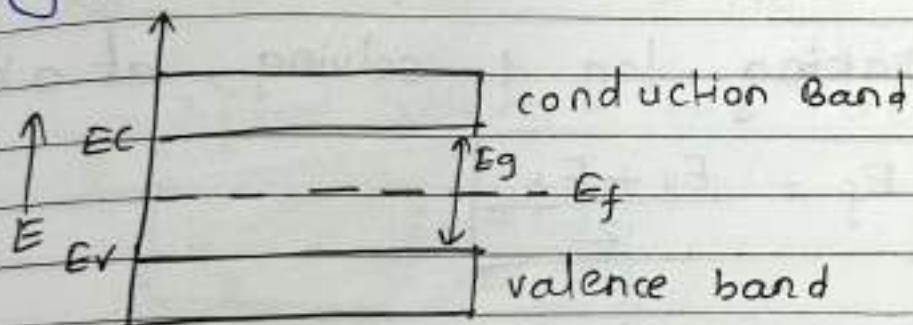
After solving this we get

$$e^{(E_c + E_v - 2E_f)/kT} = 1$$

$$\frac{E_c + E_v - 2E_f}{kT} = 0$$

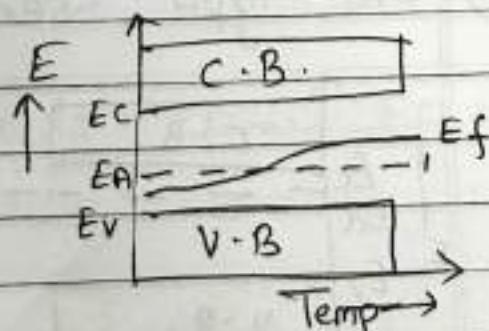
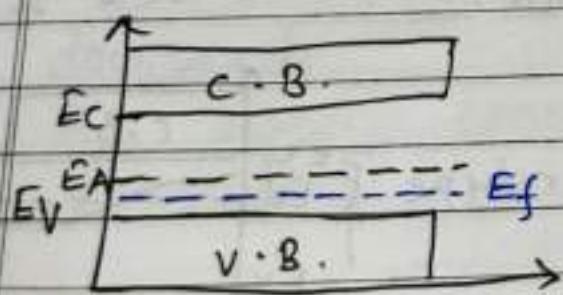
$$E_f = \frac{E_c + E_v}{2}$$

Thus fermi level in intrinsic semiconductors is exactly in the middle of the forbidden gap.



Position of fermi level in extrinsic semiconductors.

(1) P type semiconductor



carrier concentration = density function \times prob
(carrier conc. function) \times prob

EA - Energy of acceptor
Ev - Energy of valence band.

The concentration of ionised acceptors

$$p = N_A \cdot e^{(E_f - E_A)/kT} \rightarrow ①$$

N_A → carrier concentration function
& hole concentration, in valence band is,

$$p = N_V \cdot e^{(E_V - E_f)/kT} \rightarrow ②$$

N_V - carrier concentration function

Equating ① + ②

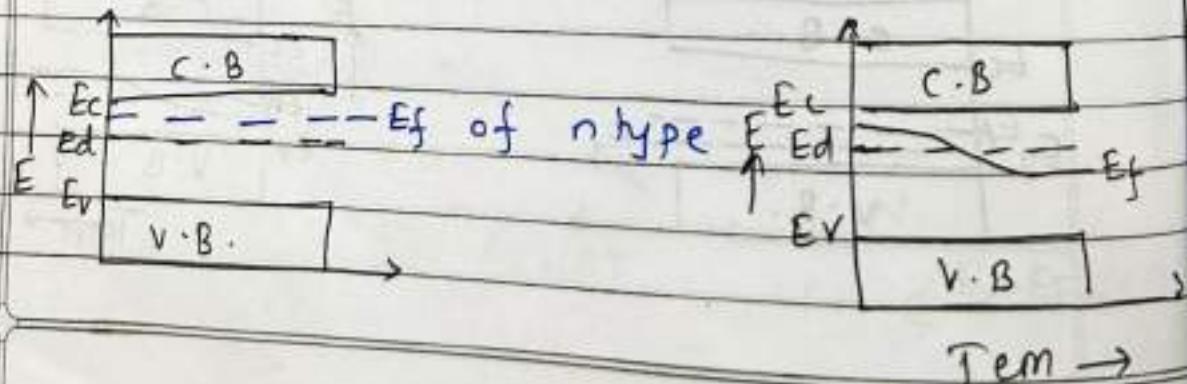
$$N_A \cdot e^{(E_f - E_A)/kT} = N_V e^{(E_V - E_f)/kT}$$

Taking log & solving, at 0 K

$$E_f = \frac{E_V + E_A}{2}$$

P type Fermi level lies midway between the top of the valence band & acceptor level. As temp. increases E_f shifts upwards. As doping concentration N_A increases Fermi

(2) N type semiconductor:- Fermi level shift down



$E_d \rightarrow$ energy of donors

$E_c \rightarrow$ Energy of conduction band.

The concentration of ionised donors

$$N = N_d \cdot e^{(E_d - E_f)/kT} \rightarrow ①$$

& electron concentration in conduction band.

$$N = N_c \cdot e^{(E_f - E_c)/kT} \rightarrow ②$$

Equating ① + ②

$$N_d \cdot e^{(E_d - E_f)/kT} = N_c e^{(E_f - E_c)/kT}$$

After solving this at 0K

$$\boxed{E_f = \frac{E_c + E_d}{2}}$$

The fermi level lies mid way between donor impurity levels and bottom of the conduction band.

As temperature increases E_f shift downwards.

As doping concentration N_d increases E_f shifts upwards.

Q) Find the temp at which there is 1.0% probability that a state with an energy 0.5 eV above fermi energy will be occupied.

$$P(E) = 1\% = 0.01$$

$$E - E_f = 0.5 \text{ eV} = 0.5 \times 1.6 \times 10^{-19}$$

$$= 8 \times 10^{-20} \text{ J}$$

$$k = 1.38 \times 10^{-23} \text{ J/K}$$

$$P(E) = \frac{1}{1 + e^{(E - E_f)/kT}}$$

$$0.01 = \frac{1}{1 + e^{(8 \times 10^{-20}) / (1.38 \times 10^{-23} \times T)}}$$

$$0.01 = \frac{1}{1 + e^{(5797.1) / T}}$$

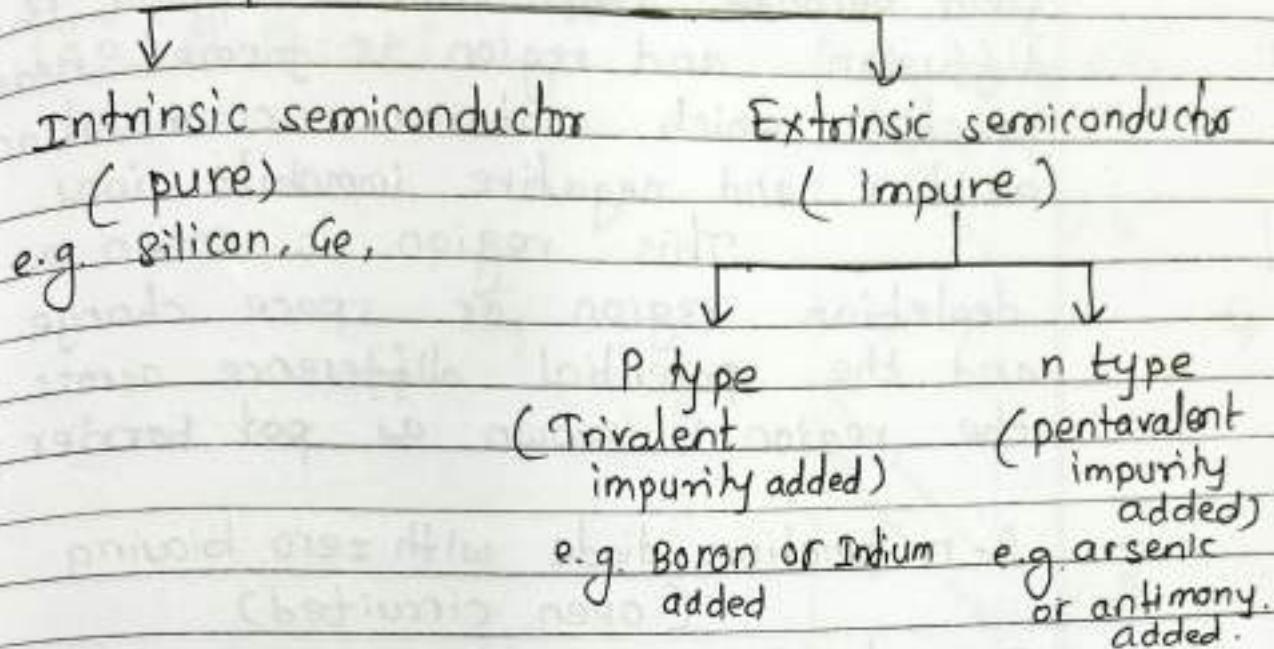
$$1 + e^{\frac{(5797.1)}{T}} = 100$$

$$e^{\frac{5797.1}{T}} = 99$$

$$\frac{5797.1}{T} = 4.595$$

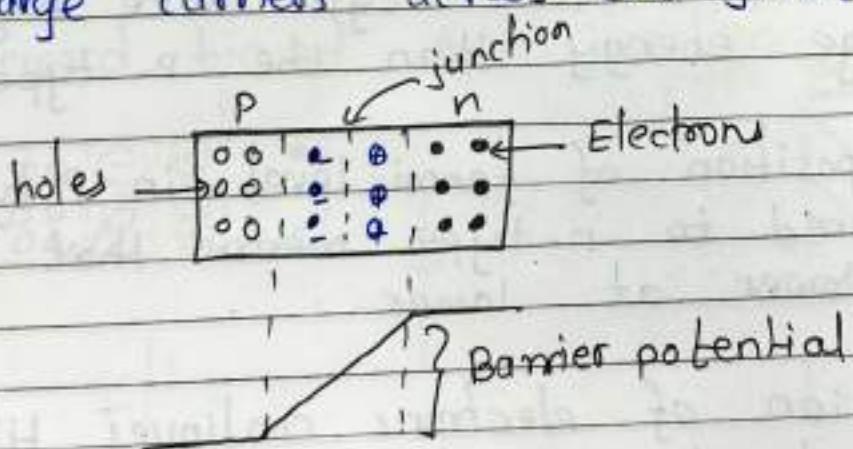
$$T = 1261.6 \text{ K}$$

Semiconductors



P-n junction Diode

When a junction is formed with p-type semiconductor on one side and n-type on other side, there is density gradient of charge carriers across the junction.



Free electrons from n type diffuse into p type & holes from p type come towards n-type.
thus positive ions are formed in n-type and negative ions at p type.

Under equilibrium conditions, the electric field becomes sufficient to oppose the diffusion and region is formed near the junction which contains accumulation of positive and negative immobile ions.

This region is known as the depletion region or space charge region, and the potential difference across the region is known as potential barrier potential.

p-n junction diode with zero biasing
(open circuited)

Fermi level is close to the conduction band in n type & close to the valence band in p type.

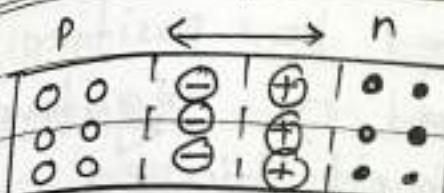
When p & n type are in contact, the electrons in n-type have higher average energy than the p-type.

The position of fermi level in p type compared to n-type means that there are lower at lower.

Diffusion of electrons continues till the fermi levels are equilibrated across the junction.

The energy bands of n type shift downward & that of p type shift upward and they shows alignment at equilibrium.

depletion



p type

c. B.

depletion

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n-type

E_f

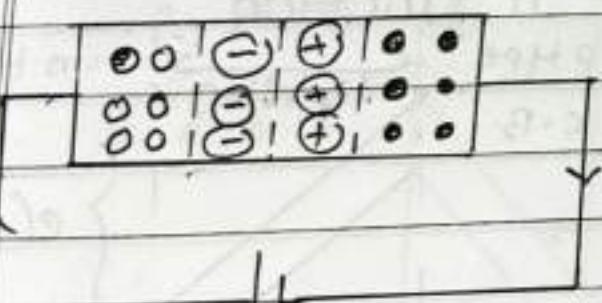
E_f

V. B.

V. B.

under the equilibrium condition fermi level is constant throughout the diode which is close to the valence band in p-type & close to the conduction band in n-type.

forward biased p-n junction:-



p type $\xrightarrow{\text{depletion}}$ n type

c. B.

$e(V_B - V)$

V. B.

E_f

E_f

c. B.

V. B.

Date: _____
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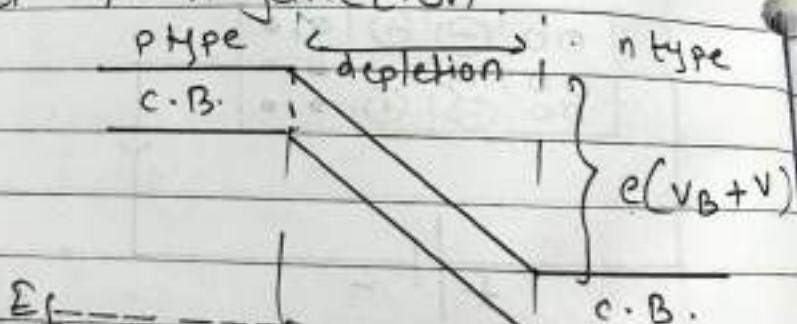
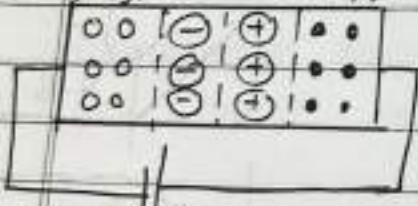
When p-type connected to positive terminal and n type connected to negative terminal of battery, called forward biased.

Electrons are removed from p-type by positive terminal of battery, which lowers the fermi level, p side.

Electrons are supplied to n-type by negative terminal of battery which raises the fermi level of n type side. If V is applied potential, energy difference reduced to $e(V_B - V)$. Due to reduced barrier potential, electrons can cross the junction $V > V_B$ and conduction takes place in diode. Diode conducts in forward biased condition.

Reversed biased p-n junction.

p type $\xrightarrow{\text{depl}}$ n type



$$V \cdot B. \quad f_f \quad V \cdot B.$$

$$V \cdot B.$$

When P type is connected to negative terminal & n type is connected to positive terminal, called reversed biased.

Negative terminal supplies free electrons into P type which raises the fermi level in P-side.

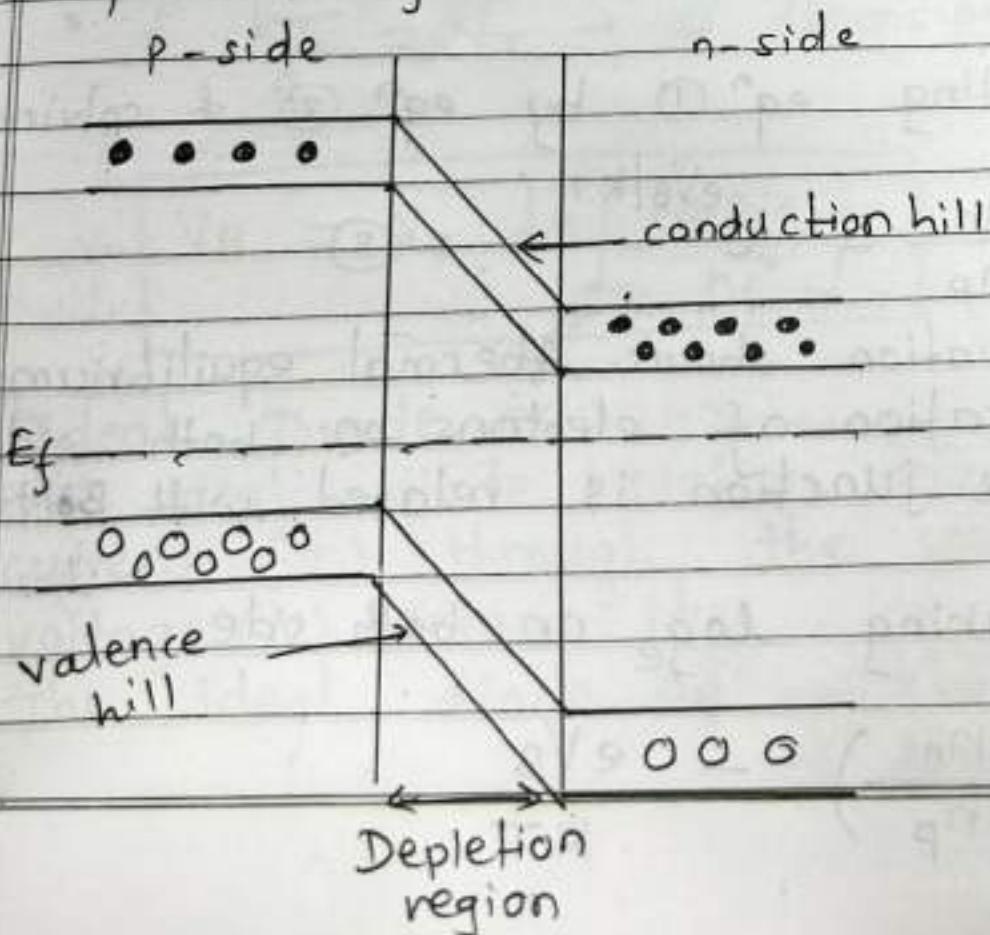
positive terminal lowers the fermi level in n-side.

small current is observed (nA) because of carriers. But displacement of charge carriers is in opposite side, which increases the width of the depletion region.

∴ Energy difference increases to $e(V_B + V)$

The free electrons in n type now faces a larger potential barrier and the diode does not conduct.

expression for Barrier potential:-



Barrier potential V_B can be determined by carrier densities in N & P region. Consider equilibrium condition, (unbiased) Fermilevel in the diode is throughout close to valence band in P type and close to conduction band in n type.

concentration of electrons in the conduction band in n-side is,

$$n_n = N_c e^{(-E_g - E_f)/kT}$$

$$n_n = N_c e^{(E_f - E_g)/kT} \rightarrow ①$$

Similarly, concentration of electrons in the conduction band in P-type

$$n_p = N_c e^{(-(E_g + eV_B) - E_f)/kT} \rightarrow ②$$

Dividing eqn ① by eqn ② & solving it

$$\frac{n_n}{n_p} = e^{eV_B/kT} \rightarrow ③$$

* Equation shows thermal equilibrium, concentration of electrons on both sides of the junction is related with Boltzmann factor.

Taking loge on both side

$$\ln\left(\frac{n_n}{n_p}\right) = \frac{eV_B}{kT}$$

$$V_B = \frac{KT}{e} \ln \left(\frac{n_n}{n_p} \right)$$

$$V_B = \frac{KT}{e} \ln \left(\frac{n_n \cdot P_p}{n_p \cdot P_p} \right) \rightarrow ④$$

$P_p \rightarrow$ acceptor concentration = N_A
(hole in P type)

$n_n \rightarrow$ donor concentration = N_D
(electrons in n type)

From law of mass action

$n_p \cdot P_p = n_i^2$ = holes in P type and ~~electrons~~ in n type at equilibrium.

$$V_B = \frac{KT}{e} \ln \left[\frac{N_D N_A}{n_i^2} \right]$$

$\frac{KT}{e} = V_T \rightarrow$ as dimensions of voltage

$$V_B = V_T \ln \left[\frac{N_D N_A}{n_i^2} \right]$$

Ideal Diode equation:-

The ideal diode equation relates the current (I) through the diode with the voltage (V) across it.

The ideal diode eqn \rightarrow Shockley ideal eqn
 \rightarrow diode law

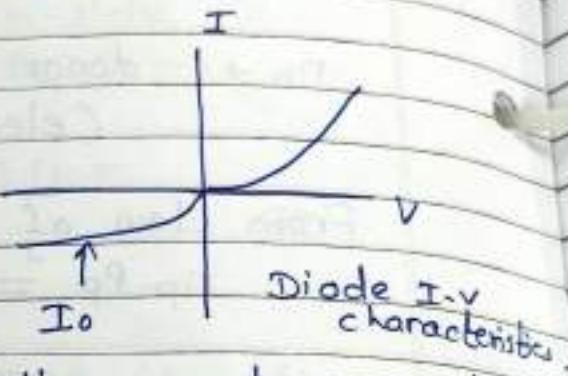
$$I = I_0 \left(e^{\frac{eV_B}{kT}} - 1 \right)$$

$I_0 \rightarrow$ reverse saturation current
 $V_B \rightarrow$ Barrier potential

$\frac{kT}{e} \rightarrow$ volt equivalent temp. = V_T

$T \rightarrow$ absolute temp.

$$V_T = \frac{T}{11600}$$



In forward biased current rises exponentially and current flows from P to n type.

$$I = I_0 e^{v/nV_T}$$

In Reversed biased

As V_T is very small, small reverse saturation current is observed. -ve sign indicates flow from n to P.

$$I = \sim I_0$$

Ideal diode Equation:-

Derivation:-

Under equilibrium condition,
the electrons in the c. B. on P side of the junction.

$$n_p = n_n \cdot e^{(-eV_B/kT)} \rightarrow ①$$

V_B → Barrier potential.

Under forward biased condition,

$$V_B \rightarrow V_B - V$$

The electrons in the c. B. on P side, in forward biasing

$$n_p^* = n_n \cdot e^{(-e(V_B-V)/kT)}$$

$$n_p^* = n_n e^{(-eV_B/kT)} \cdot e^{(eV/kT)}$$

from eqⁿ

$$n_p^* = n_p \cdot e^{(eV/kT)} \rightarrow ②$$

This shows probability of majority of charge carrier concentration crossing the junction and

diffusion current density is increased by the factor of $e^{eV/kT}$

Thus enhanced hole diffusion current density in the forward biased

$$J_{hp}^* = J_{hp} e^{eV/kT} \rightarrow ③$$

Under equilibrium condition.

$$J_{hp} = J_{hn} + J_{ep} = J_{ep}$$

Hence

$$J_{hp}^* = J_{hn} e^{eV/kT} \rightarrow ④$$

J_{hn} \rightarrow hole drift current density in n-side because of holes.

Similarly,

enhanced electron diffusion current density,
 $J_{en}^* = J_{en} e^{eV/kT} = J_{ep} e^{eV/kT} \rightarrow ⑤$

J_{ep} electron drift current density

Net ~~current~~ hole current density,

$$J_h = J_{hp}^* - J_{hn} = J_{hn} (e^{eV/kT} - 1) \rightarrow ⑥$$

Net electron current density,

$$J_e = J_{en}^* - J_{ep} = J_{ep} (e^{eV/kT} - 1) \rightarrow ⑦$$

The total current density, $J = J_h + J_e$

$$J = J_0 (e^{eV/kT} - 1) \rightarrow ⑧, J_0 \rightarrow \text{Reverse}$$

$$\therefore [J = J_0 (e^{eV/kT} - 1)] ; J_0 \rightarrow \text{saturation current}$$

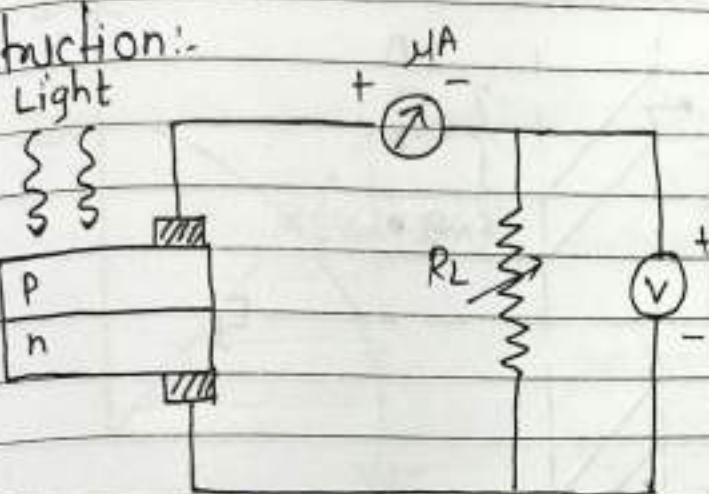
Ideal diode eqⁿ. or rectifier eqⁿ.

Applications of p-n junction

solar cell:-

solar cell or photovoltaic cells are based on the principle of photo-electric effect i.e. photon energy is converted into electrical energy:-

construction:-



It is a p-n junction with a large surface area as compared to p-n junction diodes.

p layer is very thin

mA → microammeter

V → voltmeter

RL → Load resistance.

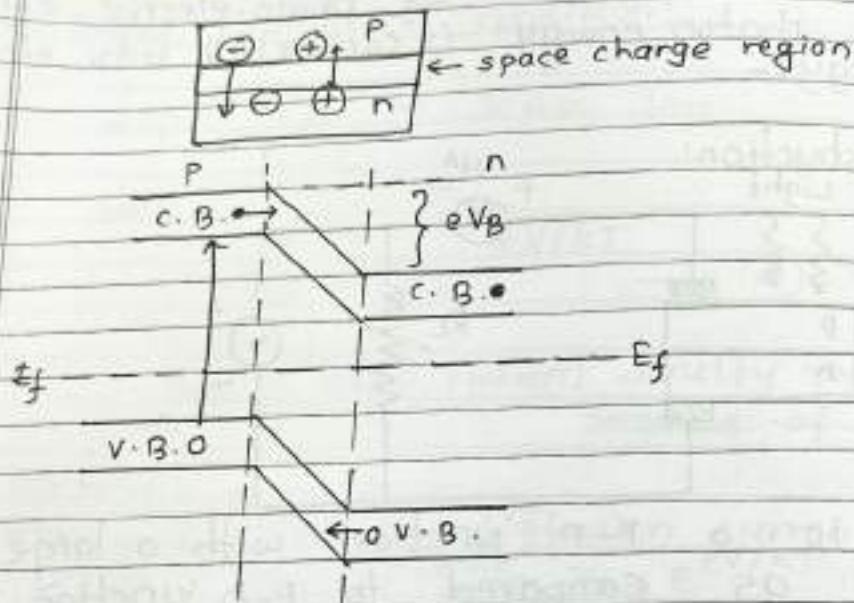
Working:-

When a p-n junction is exposed to sunlight photons of energy $h\nu$ are absorbed, if $h\nu$ is greater than the band gap Eg.

Electrons-holes pairs are generated in both the p-side and n-side of the junction, in a very small region.

But due to barrier potential, separates the electron-hole pairs.

Electrons from P side slides towards N side and holes in N-side moves towards P side



Because of the charge transfer, diffusion takes place.

Potential difference develops across the solar cell which is proportional to the intensity of light.

If an external load resistance is connected across the cell, current flows through the load. And power is generated.

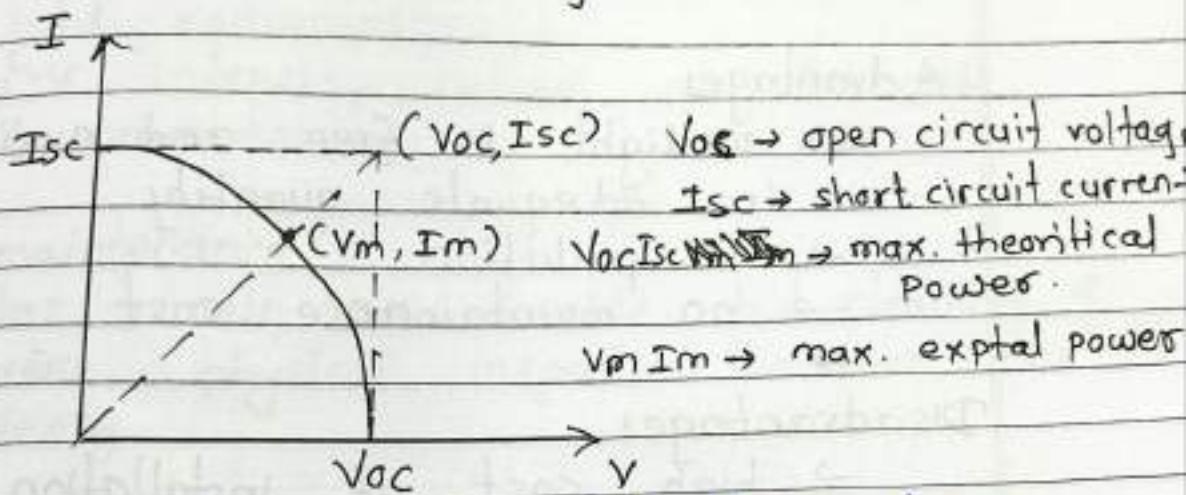
When load resistance is infinite, no current flows through it, $R_L = \infty$

And maximum voltage appears across

the solar cell called open circuit voltage V_{oc}

If $R_L = 0$, maximum current flows through it which is called short circuit current I_{sc} .

I-V characteristics of solar cell.



The typical I-V characteristics shows the graphical presentation of current + voltage

fill factor of the solar is defined as the ratio of experimental maximum power to the ideal power.

OR
FF is the ratio of usable power to ideal power.

$$FF = \frac{V_{oc} \times I_{sc}}{V_m I_m}$$

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}}$$

Materials.

Silicon, GaAs, CuInSe₂ are used in solar cell fabrication.

- those must have band gap \sim 1ev to 2eV
- have high optical absorption
- high electrical conductivity
- Easily available & low cost.

Advantages

- sunlight is free and available in adequate quantity
- no pollution
- no maintenance cost
-

Disadvantages

- high cost of installation
- low efficiency
- In cloudy days & night time difficult to use.

factors affecting on efficiency of solar cell.

OR

Ways of improving efficiency of solar cell.

1) fill factor

fill factor is utilization of available surface area, it depends on shapes of surface

2) solar cell Glazing:-

for protection of solar cell from rain, birds
surface coating is used.

surface coating treatments reduce reflections for even higher transmissivity.

solar

rev to rev.
on

t.

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cult

1.

(3) Solar panel orientation:-

If panels are perpendicular to sun rays it gives highest output.

(4) Light concentrators:-

50% intensity raised can be with light concentrators.

(5) Maintenance:-

Solar panels are durable, but cleaning & frequent physical inspection improve the efficiency.

(6) MPPT (maximum power point tracking)
This is controller which improves efficiency of system, tracking & keeping panel safe from damaging and over charging.

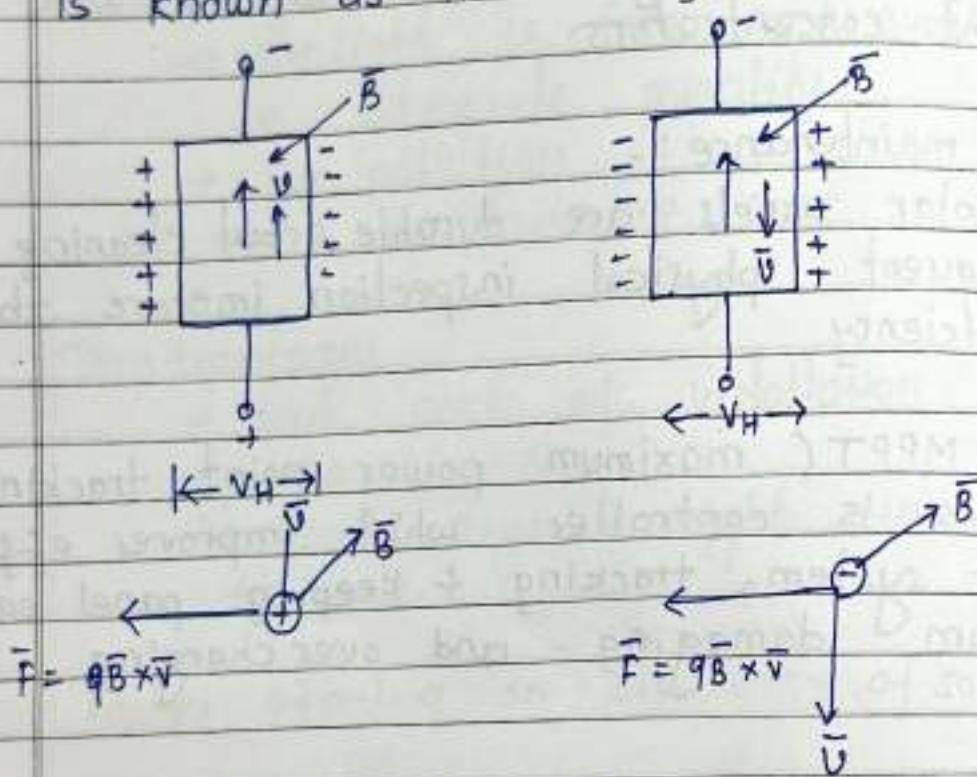
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Applications:-

- 1) Solar cells are used in satellites, space vehicles and in remote places as source of energy
- 2) battery charging system, outdoor lighting telecommunication system
- 3) In calculators for power consumption
- 4) In wrist watches
- 5) Defence equipments with solar cells.

Hall effect :-

When magnetic field is applied perpendicular to direction of current in a conductor, a potential difference develops along an axis perpendicular to both current and magnetic field. This effect is known as Hall effect, and potential difference developed is known as Hall voltage.

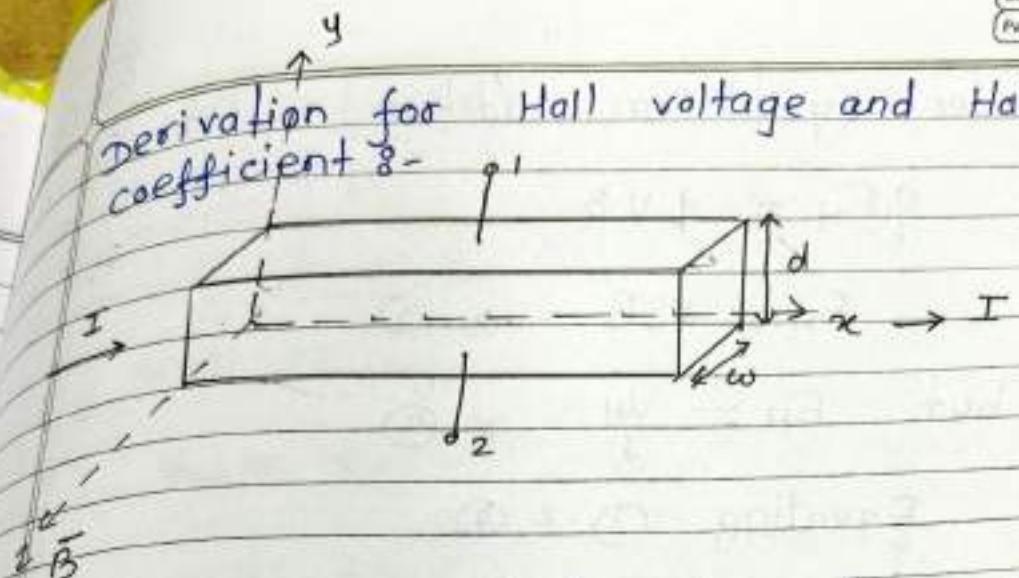


Opposite polarity of hall voltage will be developed for the two types of charge carriers for the same direction of current and magnetic field.

Hall effect is used to find the polarity of charge carriers and hence to find whether a given semiconductor is p type or n type.

derivation for Hall voltage and Hall coefficient :-

perpendicular
conductor
flowing an
current and
developed



consider a conductor th with cross section of dimensions $w \times d$. current I flows along x axis magnetic field B is applied along z axis

According to Hall effect, Hall voltage develops along y -axis (at terminal 1+2)

$V_H \rightarrow$ Hall voltage

$E_H \rightarrow$ corresponding electric field.

$v \rightarrow$ drift velocity.

Force on charge carriers due to magnetic field is

$$f = q v \cdot B \rightarrow ①$$

Force due to the electric field related to Hall voltage is

$$f = q E_H \rightarrow ②$$

Equating ① + ②

under equilibrium condition,

$$qE_H = qVB$$

$$E_H = V \cdot B \rightarrow ③$$

$$\text{but } E_H = \frac{V_H}{d} \rightarrow ④$$

Equating ③ + ④

$$\frac{V_H}{d} = V \cdot B$$

$$V_H = V \cdot B \cdot d \rightarrow ⑤$$

current flowing through the conductor is,

$$I = n \cdot q \cdot a \cdot V$$

$$\therefore V = \frac{I}{n \cdot q \cdot a} \rightarrow ⑥$$

substituting ⑥ in ⑤

$$V_H = \frac{B \cdot d \cdot I}{n q a}$$

$$\text{but } a = \omega \times d \quad \therefore \frac{d}{a} = \frac{1}{\omega}$$

$$\therefore V_H = \frac{I \cdot B}{n \cdot q \cdot \omega} \rightarrow ⑦$$

The quantity $\frac{1}{nq}$ is reciprocal of charge density nq . It is defined as Hall coefficient.

Hall coefficient

$$R_H = \frac{1}{nq} \quad \rightarrow \textcircled{8}$$

from eqⁿ $\textcircled{7}$

$$V_H \propto R_H \cdot I \cdot B$$

$$V_H = R_H \cdot \frac{I \cdot B}{a}$$

or

$$V_H = R_H \cdot \frac{I \cdot B \cdot d}{a}$$

this is the expression for Hall voltage

If E is the electric field to produce current, V , is the applied voltage along x axis and l is the length of conductor. And E_H field along y axis.

$$E = \frac{V}{l}$$

$$\& \quad E_H = V \cdot B = \frac{B \cdot I}{nqa}$$

$$\frac{E_H}{E} = \frac{B \cdot I}{nqa} \cdot \frac{l}{V}$$

$$\frac{E_H}{E} = \frac{B}{nq \cdot a} \times \frac{l}{R} \quad \dots R = \frac{V}{I}$$

$$\text{but } g = \frac{Ra}{l}$$

$$\boxed{\frac{E_H}{E} = \frac{B}{nq.s}}$$

the angle made by the resultant electric field with the x-axis is known as the Hall angle (θ_H)

$$\boxed{\tan \theta_H = \frac{E_H}{E} = \frac{B}{nq.s}}$$

By knowing charge density, we can determine mobility of charge carriers

$$b = n \cdot q \cdot \mu$$

$$\boxed{b = \frac{\mu}{R_H}} \quad \text{or} \quad \boxed{\rho = \frac{R_H}{\mu}}$$

$$\cancel{\tan \theta_H = \frac{B \cdot q}{b}}$$

$$\boxed{\tan \theta_H = \frac{B \cdot b}{nq}}$$

$$\boxed{\tan \theta_H = B \cdot M}$$

thus Hall effect can be used to determine

- ① whether semiconductor is P type or n type
- ② Density of charge carriers
- ③ Mobility of charge carriers.

17) calculate the mobility of charge carriers in a doped silicon whose conductivity is 100 per $\Omega^{-1} \text{m}^{-1}$ and the Hall coefficient is $3.6 \times 10^{-4} \text{ m}^3/\text{coulomb}$.

$$b = 100 \text{ per } (\Omega^{-1}\text{m})^{-1}$$

$$R_H = 3.6 \times 10^{-4} \text{ m}^3/\text{C}$$

$$\mu = b \cdot R_H$$

$$\mu = 100 \times 3.6 \times 10^{-4}$$

$$\boxed{\mu = 3.6 \times 10^{-2} \text{ m}^3/\text{V}\cdot\text{s}}$$

(2) A slab of copper 2.0mm in thickness and 1.5 cm wide is placed in a uniform magnetic field with magnitude 0.40 T. When a current of 75 amp. flows along the length, the voltage measured across the width is 0.81 μV . Determine the concentration of mobile electrons in copper.

Given,

$$B = 0.4 \text{ T}$$

$$I = 75 \text{ A}$$

$$d = 1.5 \text{ cm} = 1.5 \times 10^{-2} \text{ m}$$

$$V_H = 0.81 \mu\text{V} = 0.81 \times 10^{-6} \text{ V}$$

$$q = 1.6 \times 10^{-19} \text{ C}$$

$$a = 2 \text{ mm} = 2 \times 10^{-3} \text{ m}$$

$$V_H = \frac{B \cdot I \cdot d}{n \cdot q \cdot a}$$

$$n = \frac{B \cdot I \cdot d}{V_H \cdot q \cdot a}$$

$$= \frac{0.4 \times 75 \times 1.5 \times 10^{-2}}{0.81 \times 10^{-6} \times 1.6 \times 10^{-19} \times 3 \times 10^{-5}}$$

$$n = 1.157 \times 10^{29} \text{ per m}^3$$

3) calculate the number of acceptors to be a Germanium sample to obtain the resistivity of 10^{-2} cm . $\mu = 1700 \text{ cm}^2/\text{V}\cdot\text{s}$.

$$\rightarrow \mu = 1700 \text{ cm}^2/\text{V}\cdot\text{s}$$

$$\rho = 10^{-2} \text{ cm}$$

$$f = n \cdot e \cdot \mu$$

$$\frac{1}{\rho} = \frac{n \cdot e \cdot \mu}{\cancel{f} \cancel{e/m}} \quad \cancel{f \cdot e/m}$$

$$\therefore n = \frac{1}{e \cdot \mu \cdot \rho}$$

$$= \frac{1}{1.6 \times 10^{-19} \times 1700 \times 10}$$

$$n = 3.6 \times 10^{14} \text{ /cm}^3$$

The Hall coefficient of a specimen of doped silicon is found to be $3.66 \times 10^{-3} \text{ m}^3/\text{C}$. The resistivity of the specimen is $8.93 \Omega\text{-m}$. Determine the mobility of charge carriers.

Given

$$\rho_{RA} = 8.93 \Omega\text{-m}$$

$$R_H = 3.66 \times 10^{-3} \text{ m}^3/\text{C}$$

$$R_H = \frac{1}{n \cdot q} = \frac{1}{n \cdot e}$$

$$\delta = n \cdot q \cdot u = n \cdot e \cdot u$$

$$\rho = \frac{1}{n \cdot e \cdot u}$$

$$\rho = \frac{R_H}{u} \quad \therefore u = \frac{R_H}{\rho}$$

$$u = \frac{3.66 \times 10^{-3}}{8.93}$$

$$u = 4.098 \times 10^{-4} \text{ m}^2/\text{N}\cdot\text{s}$$

Unit - 4

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Date	

Question Bank

- (1) Define $\langle a \rangle$ drift velocity $\langle b \rangle$ mean free path
 $\langle c \rangle$ drift current $\langle d \rangle$ diffusion current
 $\langle e \rangle$ fermi level $\langle f \rangle$ effective mass
 $\langle g \rangle$ density of states $\langle h \rangle$ [8]
- (2) State the assumptions of classical free electron model. Give success and failure of free electron theory. [6]
- (3) Explain classification of solids on the basis of band theory. [4]
- (4) What is fermi level? Explain - fermi Dirac probability distribution function [4]
- (5) Derive an expression for conductivity of conductors [6]
- (6) Derive an expression for conductivity of intrinsic and extrinsic semiconductors. [6]
- (7) Using expression for concentration of charge carriers in n-type semiconductor, derive expression for the position of fermi level. Explain its variation with temperature. [6]
- (8) Explain the formation of depletion region in a semiconductor diode. Derive expression for barrier potential [6]
- (9) Derive an ideal diode equation of P-n junction
- (10) Explain Hall effect in semiconductors. Derive equation for Hall voltage and Hall coefficient.
- (11) Explain the construction and working of solar cell. Draw its IV characteristic and define its important parameters. [6]
- (12) Give any four applications of solar cell. Give any two factors affecting on efficiency of solar cell. [6]