EnggTree.com

SIMPLE CUBIC STRUCTURE

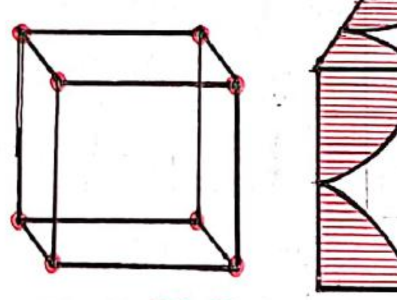
* It is the simplest form of Crystal structure.
* There are 8 atoms at all 8 corners of the unit cell.
* Corner atoms touch with each other.

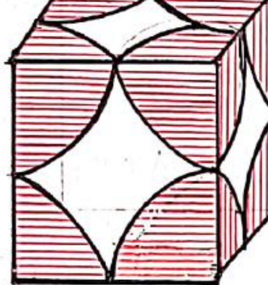
No OF ATOMS PER UNIT CELL

* Total no. of atoms presented in each corner is 8.
* Each corner atom is shared by eight adjascent unit cells.

∴ Total no. of atoms $= 8 \times \frac{1}{8} = 1$

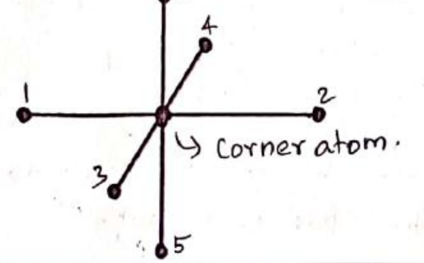
Total no. of atoms per unit cell $= \boxed{1}$





Co-Ordination No:

It is the no. of nearest atoms directly saurrounding a particular atom in a crystal.

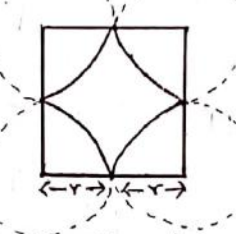


In SC system each corner atom is saurrounded by 6 nearest Corner atoms along it's axes.

∴ The Coordination no $= \boxed{6}$

Atomic Radius:

* It is half the distance between any two nearest neighbouring atoms in a crystal (r)
* Here any 2 corner atom has a closest bond.



$2r = a$

$\boxed{r = \frac{a}{2}}$

* The distance between the centre of the atoms is equal to the side of a cube.

Atomic Packing Factor:

$$APF = \frac{\text{No. of atoms per unit cell} \times \text{Vol. of atom}}{\text{Volume of an unit cell.}}$$

No of atom $= 1$

Vol of atom $= \frac{4}{3}\pi r^3$ $\qquad r = a/2$

Vol. of unit cell $V = a^3$

$$APF = \frac{1 \times \frac{4}{3}\pi (a/2)^3}{a^3} = \frac{4\pi a^3}{3 \times a^3 \times 8} = \frac{\pi}{6}$$

$\boxed{APF = 52\%}$

In SC unit cell 52% free space occupied by atoms. Remaining 48% volume is vaccant.

Downloaded from EnggTree.com

Scanned with CamScanner

EnggTree.com

BODY CENTERED CUBIC STRUCTURE

* In BCC unit cell, 8 corner atoms and 1 body center atom are available
* Each corner atom is shared by 8 adjacent unit cells.
* Body center atom completely belongs to a single unit cell.

No of Atoms per unit cell:

Corner atom $= 8 \times \frac{1}{8} = 1$

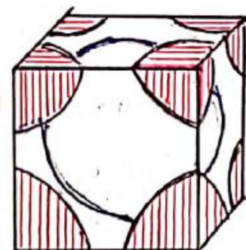
Body center atom $= 1$

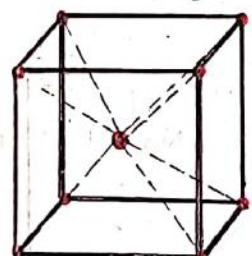
∴ Total no. of atoms per unit cell $= 1+1 = \boxed{2}$

Co-ordination Number:

In BCC each body centered atom is surrounded by 8 closest corner atom along its diagonal.

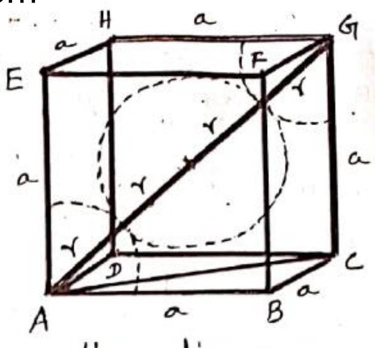
∴ Coordination Number = 8





Atomic Radius: (r)

* In BCC, Closest and longest bond Consider between any two corner atoms and Body center atom along its body diagonal.
* From the diagram consider a body diagonal 'AG' of an unit cell.



From the diagram

$\Delta ACG \quad AG^2 = AC^2 + CG^2$

Wkt, $AG = 4r$, $CG = a$

and $AC^2 = AB^2 + BC^2$

In which, $AB = a$, $BC = a$

$\therefore AG^2 = AB^2 + BC^2 + CG^2$

$(4r)^2 = a^2 + a^2 + a^2$

$16r^2 = 3a^2$

$r^2 = \frac{3}{16} a^2 \Rightarrow \boxed{r = \frac{\sqrt{3}}{4} a}$

Atomic Packing Factor

$$PF = \frac{\text{No. of atoms per unit cell} \times \text{Vol. of an atom}}{\text{Volume of an unit cell.}}$$

No of atoms per unit cell = 2

∴ Atomic Radius $r = \frac{\sqrt{3}}{4} a$

Volume of an unit cell $V = a^3$

$$\therefore PF = \frac{2 \times 4/3 \pi r^3}{a^3}$$

$$= \frac{2 \times 4/3 \pi \left(\frac{\sqrt{3}}{4} a\right)^3}{a^3}$$

$$= \frac{2 \times 4 \times \pi \times 3 \times \sqrt{3} \times a^3}{3 \times 4 \times 4 \times 4 \times a^3}$$

$$PF = \frac{\sqrt{3}\pi}{8} = 0.68$$

So in BCC, 68% space in an unit cell occupied by atoms and 32% of the space is vacant.

CHENNAI INSTITUTE OF TECHNOLOGY DEPT. OF SCIENCE AND HUMANITIES CHENNAI 69

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

Face CENTERED CUBIC (FCC)

* In FCC, structure, the unit cell has 8 corner atoms and one atom at the centre of each face.

* It is one of the Closely Packed structures

No of Atoms per unit cell:

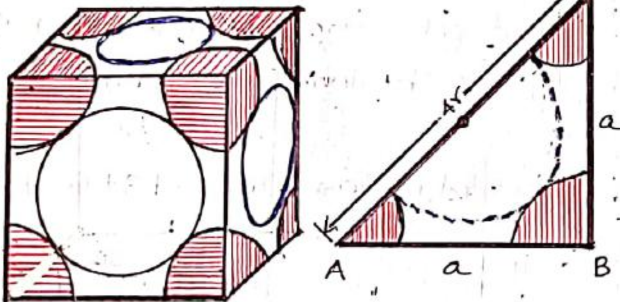
* In FCC unit cell, Corner atom is shared by 8 adjacent unit cells.

∴ No. of corner atoms $= 8 \times \frac{1}{8} = 1$

* Each Face center atom shared by 2 other unit cells.

∴ No of face center atoms $= 6 \times \frac{1}{2} = 3$

∴ Total no. of atoms per unit cell $= 1 + 3 = \boxed{4}$



Co-ordination Number:-

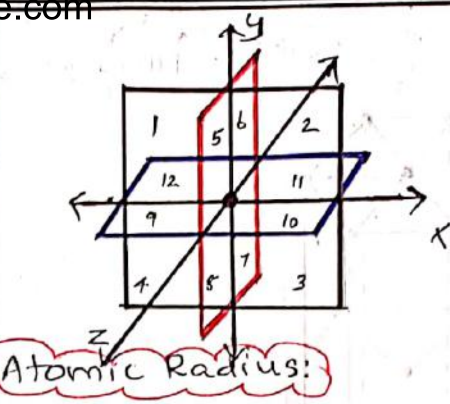
* In FCC, each corner atom surrounded by 4 face center atom in an axis plane [x, y, z]

X-plane [1,2,3,4], Y-plane [5,6,7,8]

Z-plane [9,10,11,12]

∴ Total no. of nearest atoms

$= 4 + 4 + 4 = 12$



Atomic Radius:

In FCC, each face center atom has a bond between two corner atom through its face diagonal.

In ΔABC $AC^2 = AB^2 + BC^2$

$$(4r)^2 = a^2 + a^2$$

$$16r^2 = 2a^2$$

$$r^2 = \frac{2a^2}{16}$$

$$r = \frac{\sqrt{2}a}{4}$$

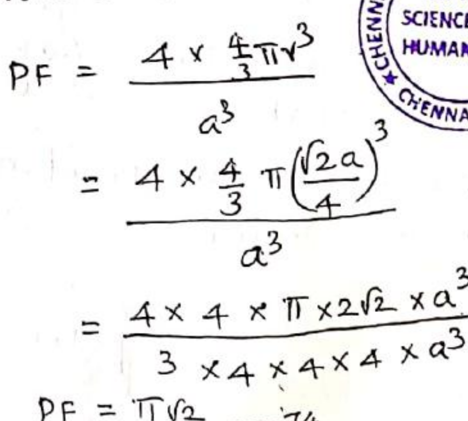
Atomic Packing Factor:-

$$PF = \frac{\text{No. of atoms Per unit cell} \times \text{Vol. of 1 atom}}{\text{Volume of an unit cell}}$$

No. of atoms $= 4$

Radius $r = \frac{\sqrt{2}a}{4}$

Volume $V = a^3$



$$PF = \frac{4 \times \frac{4}{3}\pi r^3}{a^3}$$

$$= \frac{4 \times \frac{4}{3}\pi\left(\frac{\sqrt{2}a}{4}\right)^3}{a^3}$$

$$= \frac{4 \times 4 \times \pi \times 2\sqrt{2} \times a^3}{3 \times 4 \times 4 \times 4 \times a^3}$$

$$PF = \frac{\pi\sqrt{2}}{6} = 0.74$$

In FCC unit cell, 74% Volume occupied 26% is vacant.

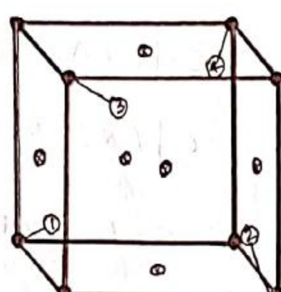
CHENNAI INSTITUTE OF TECHNOLOGY DEPT. OF SCIENCE AND HUMANITIES CHENNAI 69

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

Diamond Cubic Structure:

* Diamond is a modified form of FCC.
* It consists of 8 corner atoms, 6 face center atoms and 4 body diagonal atoms
* The body diagonal atom located either at 1/4 or 3/4 from corner atom.



- Corner atom
- Face center atom
- Diagonal atom.

* It is a loosely packed structure, since the maximum number of neighbouring atom is 4

Hence the Coordination no = 4

No. of atoms per unit cell:

Each corner atom shared by 8 adjacent unit cell.

No. of corner atom = $8 \times \frac{1}{8} = 1$

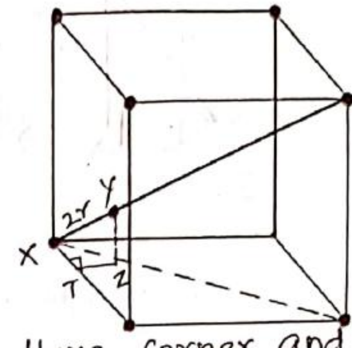
Each face centred atom is shared by two unit cells.

No. of face center atoms = $6 \times \frac{1}{2} = 3$.

4 atom present completely inside an unit cell along the diagonal = 4

∴ Total no. of atoms = 1+3+4 = 8

Atomic Radius



Here corner and the diagonal atom consider as nearest neighbouring atom. From the diagram,

In Δ XYZ

$$XY^2 = XZ^2 + YZ^2$$

In Δ XZT

$$XZ^2 = XT^2 + ZT^2$$

$$\therefore XY^2 = XT^2 + ZT^2 + YZ^2$$

$$(2r)^2 = (a/4)^2 + (a/4)^2 + (a/4)^2$$

$$4r^2 = \frac{a^2}{16} + \frac{a^2}{16} + \frac{a^2}{16} = \frac{3a^2}{16}$$

$$r^2 = \frac{3a^2}{64} \qquad r = \frac{\sqrt{3}a}{8}$$

Atomic Packing factor:

$$APF = \frac{\text{Tot. no. of atoms} \times \text{Vol. of 1 atom}}{\text{Vol. of unit cell.}}$$

$$APF = \frac{8 \times 4/3 \pi \left[\frac{\sqrt{3}a}{8}\right]^3}{a^3} = \frac{8 \times 4 \times \pi \times 3\sqrt{3} \times a^3}{3 \times 8 \times 8 \times 8 \times a^3}$$

$$APF = \frac{\pi\sqrt{3}}{16} = 0.34$$

APF = 34%

In Diamond, 34% of space is atom, and 66% of space is vacant.

CHENNAI INSTITUTE OF TECHNOLOGY DEPT. OF SCIENCE AND HUMANITIES CHENNAI 69

CHENNAI INSTITUTE OF TECHNOLOGY

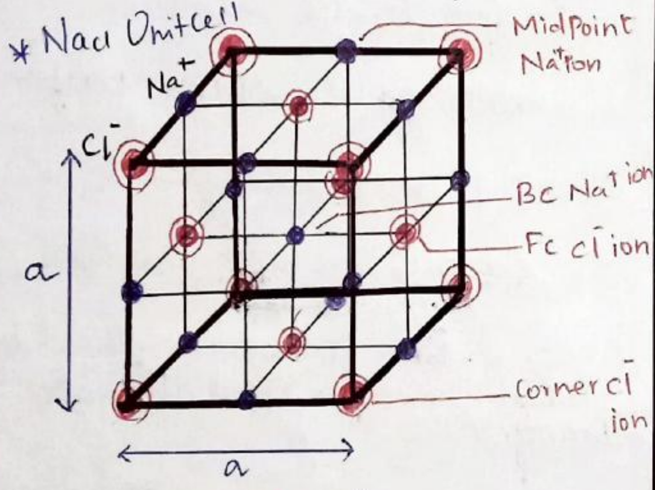
Downloaded from EnggTree.com

Scanned with CamScanner

EnggTree.com

NaCl - CRYSTAL STRUCTURE

* Sodium Chloride (NaCl) is an ionic crystal
* It has FCC Structure
* Na^+ and Cl^- ions arranged in an alternate fashion as shown in the figure.
* NaCl Unitcell



• Na^+ ◎ Cl^-

* NaCl Unitcell consists of

8 Cl^- corner ion
6 Cl^- face center ion
12 Na^+ Mid point ion
1 Na^+ Body centered ion

Thus NaCl crystal can be composed of two FCC sublattices.

Number of Atoms

(i) Number of Na^+ ions

Total no of mid point Na^+ ions 12. Each Na^+ shared by 4 adjacent Unit cells.

$\therefore$ No of mid point Na^+ ion $= \frac{1}{4} \times 12$
$= 3$ ions

Each Body centered Na^+ ion is completely belongs to each Unit cell.

$\therefore$ no of BC Na^+ ions $= 1 \times \frac{1}{1} = 1$
$= 1$ ion.

$\therefore$ Total no of Na^+ ions $= 3+1 = \boxed{4}$

(ii) No of Cl^- ions.

Totally 8 corner ~~atom~~ ions each Shared by 8 adjacent Unit cell

$\therefore$ contribution of Cl^- corner atoms $= 8 \times 1/8 = 1$

6 FC Cl^- ions contribution is
$= 6 \times 1/2 = 3$

$\therefore$ Total no of Cl^- ions

$3 + 1 = \boxed{4}$

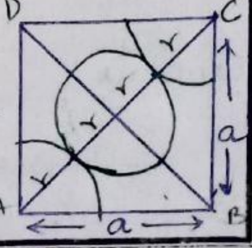
Thus there are 4 Na^+ & 4 Cl^- ions per Unit cell in a NaCl crystal.

Co-ordination no

Each Cl^- ions surrounded by 6 Nearest Na^+ ions. Similarly Each Na^+ ions surrounded with 6 Cl^- ion hence Co-ordination of NaCl crystal is $\boxed{6}$

Atomic radius

NaCl is a Type of FCC lattice from the figure w.k.that.



Downloaded from EnggTree.com

EnggTree.com

$$AC^2 = AB^2 + BC^2$$

$$(AD)^2 = a^2 + a^2$$

$$Ar = \sqrt{2a^2}$$

$$\boxed{r = \frac{a\sqrt{2}}{4}}$$

Atomic Packing factor

$$APF = \frac{\text{T. No of atom} \times \text{Vol of an atom}}{\text{Total Vol of an Unitcell}}$$

$$= \frac{4 \times \frac{4}{3}\pi r^3}{a^3} \quad \text{where } r = \frac{a\sqrt{2}}{4}$$

$$= \frac{4 \times 4 \times \pi \times a^3 \times \sqrt{2} \times \sqrt{2} \times \sqrt{2}}{3 \times 4 \times 4 \times 4 \times 4 \times a^3}$$

$$= \frac{\pi\sqrt{2}}{6} = 0.74.$$

Atomic Packing Density = 74%.

Void space is = 26%.

WAFER SURFACE:

A wafer is a thin slice of semiconductor used in microelectronics as a platform for fabrication of integrated circuits.

The wafer serves as the substrate for microelectronic devices built in and upon wafer.

In general, wafers are grown from crystal having a regular crystal structure.

Wafer Surface Orientation:

Refers to the surface alignment of the silicon wafer. It may be perpendicular to the substrate, horizontal or vertical. Orientation is defined by the miller index (100), (111) faces.

Importance:

1. The orientation of the silicon wafer is important because it affects the electronic properties and efficiency of the devices.

2. It also more important for semiconductor because it can affect the conductivity, thermal resistance and optical properties.

Downloaded from EnggTree.com

EnggTree.com

FLATS:

During the manufacturing process, silicon is cut into wafers with different Orientation. In general, the two most common types of wafer Orientations are:

- C-shaped
- Flats.

* Flats:

A flat is a visual reference to the Orientation of a wafer, which indicates the Crystal Orientation.

Types:

There are two types of flats.

(i) Primary flats.
(ii) Secondary flats.

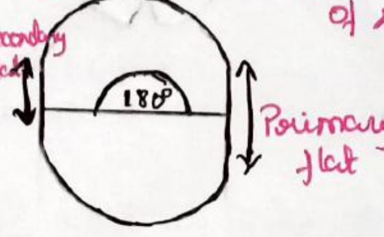
(i) Primary flats:

The primary flat has a specific Crystal Orientation relative to the wafer surface. This acts as a Visual reference to the Orientation of the wafer.

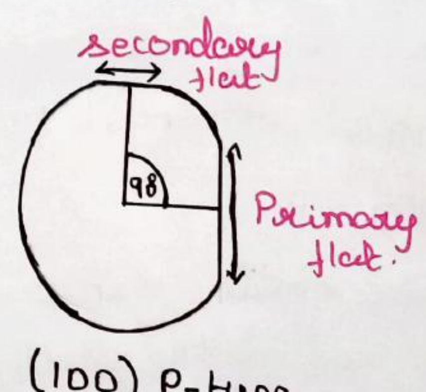
(ii) Secondary flats:

Secondary flats indicates the Crystal Orientation and it is used for identification wafers dopant type.

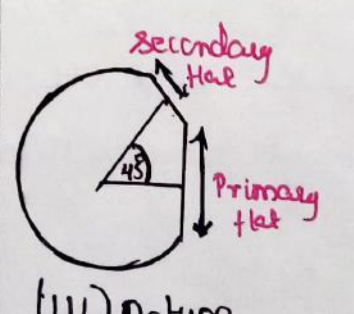
Fig shows the different Orientation of silicon wafer.



(100) n-type.



(100) P-type.



(111) n-type

Primary flat

(111) P-type

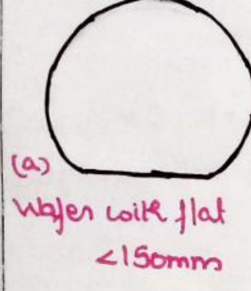
Wafers with a pair of flats at different angles convey the doping type of the semiconductor.

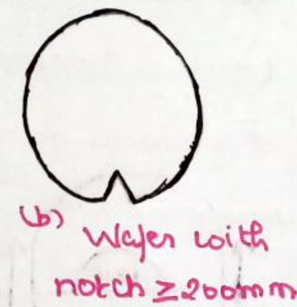
Downloaded from EnggTree.com

EnggTree.com

Notches:

A wafer notch is small cut into the wafer in order to align it in a repeatable orientation during each step of processing.


(a) Wafer with flat <150 mm


(b) Wafer with notch ≥ 200 mm

While wafers with an 8 inch diameter and above use a single notch to convey wafer orientation, which is independent from the doping type.

Wafer smaller than four inches uses two notches at different angles to indicate the orientation of the flat surface and the two-notch angle between them.

Crystal Imperfections:

If atoms in solid are not arranged in a perfectly regular manner, it is called defects.

Downloaded from EnggTree.com

EnggTree.com

Types:

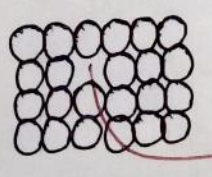
* **Point Defects**
  - Vacancies
  - Interstitial Defects
  - Impurity Defects.
  - ~~Impurit~~
* **Line Defects**
  - Edge Dislocation
  - Screw Dislocation.
* **Surface Defects**
  - Grain Boundaries
  - Tilt Boundaries
  - Twin Boundaries
  - Stacking Faults.
* **Volume Defects**
  - Crack.

Point Defects:-

Due to imperfect packing of atoms during crystallisation.

Vacancies:-

It refers to a missing atom.



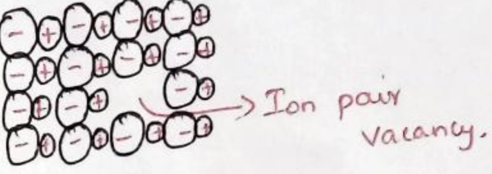
There are two types of vacancies

(i) Schottky Defect.

(ii) Frenkel Defect.

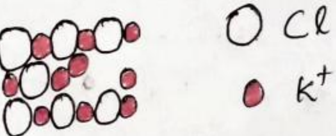
Schottky Defect:-

It refers to the missing of a pair of positive and negative ions in an ionic crystal.



Frenkel Defect:

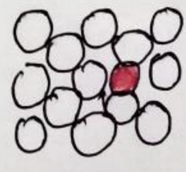
A vacancy associated with interstitial impurity is called Frenkel defect.



Interstitial Defect:

Self Interstitial

If an atom from same crystal occupies interstitial site it is called Self interstitial



Foreign Interstitial

If an impurity atom occupies interstitial site it is called foreign interstitial.

Downloaded from EnggTree.com

Impurities:

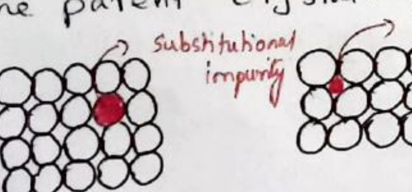
Adding of foreign atoms to Crystal lattice is known as impurity defects

Substitutional impurity Defect:

* Foreign atom replaces the parent atom

Interstitial Impurity Defect:

Small size foreign atom occupies the empty space in the parent crystal.



Line Defect:

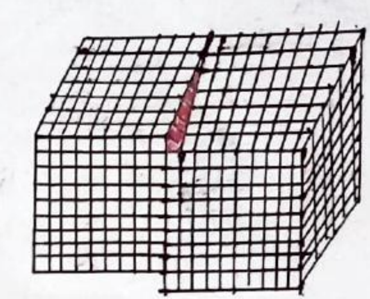
A portion of a line of atoms is missing or displaced from its regular size.

Types:

Edge Dislocation.
Screw Dislocation.

Edge Dislocation:

In this type one of the atomic planes does not extend through the entire crystal.



Screw Dislocation:

It is due to a displacement of atoms in one part of a crystal relative to rest of the crystal

Surface Defects:

In this type, the defects takes place in the surface of Crystal.

Grain Boundary:

It is the boundary in the grains at which the atomic arrangement one side is mirror image of the atoms on the other side

Tilt Boundary:

It is an array of parallel edge dislocation

Stacking Faults:

Whenever the stacking of atoms is not in proper sequence

Downloaded from EnggTree.com

EnggTree.com

Miller Indices

These are three smallest possible integers written inside the parantheses, which represent a plane or its direction [hkl]

Procedure

STEP 1: Find the Intercept made by the Plane along x, y, z axis.

STEP 2: Take the reciprocals of the intercepts.

STEP 3: Clear the fractions [convert them into Whole No by taking LCM]

STEP 4: write the integers [inside the Paranthesis without comma and quatation]

Example:

Consider a plane ABC
It intercep along x, y & z axis 2A, 2B, 3C

(Figure: plane ABC with intercepts 2A on x, 2B on y, 3C on z; axis marks 1A, 2A, 1B, 2B, 1C, 2C, 3C)

∴ Miller Indices of the Plane is written as follows.

STEP 1: Intercepts are 2, 2, 3

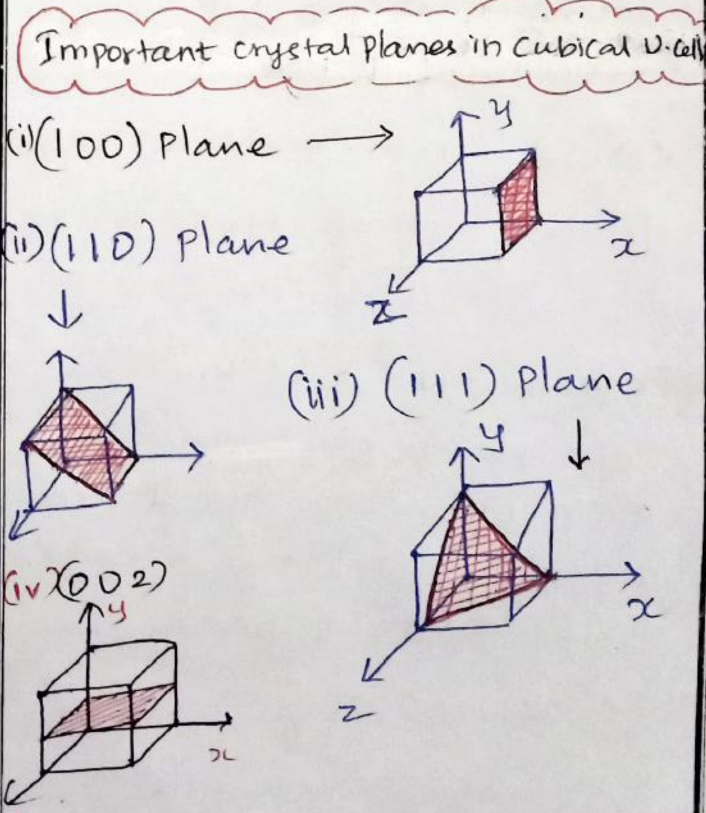
STEP 2: The reciprocal of Intercepts are $\frac{1}{2}, \frac{1}{2}, \frac{1}{3}$

STEP 3: Multiplying each term with the LCM we get (3, 3, 2)

STEP 4: The miller indices of the Plane ABC are (332)

Significance

- These are usefull in Under Standing the Shapes of single crystals.
- In the study of the microstructure of a material.
- To interpret x-ray diffraction Pattern.



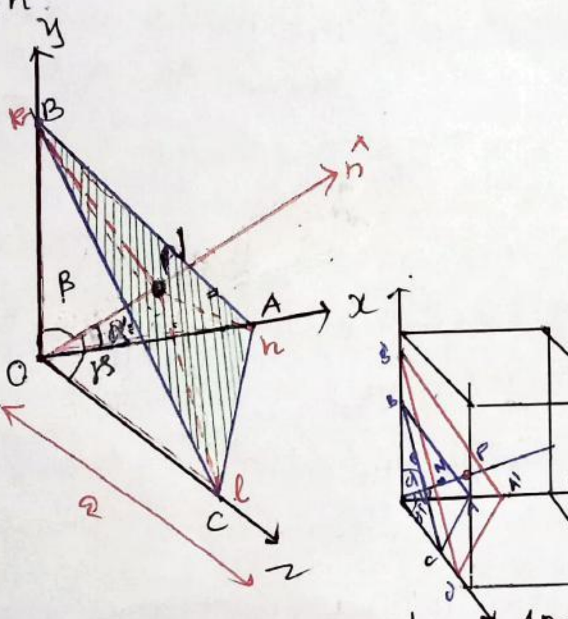
Downloaded from EnggTree.com

EnggTree.com

Inter planar distance (or) d-spacing

Definition:

It is a method used to find out the distance between any two planes (or) plane from the orgin.



* Let us consider a plane ABC intersect along x, y, and z axis at a point h, k, l (miller indices).
* Consider $\hat{n}$ is a normal line passing perpendicular to the plane ABC from the origin.
* here ON = d is know as "Inter planar distance".
* OA, OB, OC are the intercept made by the plane along x y & z axis, ∴ the miller indices are

$$OA : OB : OC = \frac{1}{h} : \frac{1}{k} : \frac{1}{l}$$

× by lattice constant 'a'

$$OA : OB : OC = \frac{a}{h} : \frac{a}{k} : \frac{a}{l}$$

* angles made by the normal line with x, y & z axis is α, β & γ respectively. Then

From the △ OAN.

$$\cos\alpha = \frac{\text{Adj Side}}{\text{Hypote}} = \frac{ON}{OA} = \frac{d}{a/h} = \frac{dh}{a}$$

$$\cos\beta = \frac{ON}{OB} = \frac{d}{a/k} = \frac{dk}{a}$$

$$\cos\gamma = \frac{ON}{OC} = \frac{d}{a/l} = \frac{dl}{a}$$

From law of cosines

$$\cos^2\alpha + \cos^2\beta + \cos^2\gamma = 1$$

$$\left(\frac{dh}{a}\right)^2 + \left(\frac{dk}{a}\right)^2 + \left(\frac{dl}{a}\right)^2 = 1$$

$$\frac{d^2h^2}{a^2} + \frac{d^2k^2}{a^2} + \frac{d^2l^2}{a^2} = 1$$

$$\frac{d^2}{a^2}(h^2 + k^2 + l^2) = 1$$

$$d^2 = \frac{a^2}{h^2 + k^2 + l^2}$$

$$\boxed{d = \frac{a}{\sqrt{h^2 + k^2 + l^2}}}$$

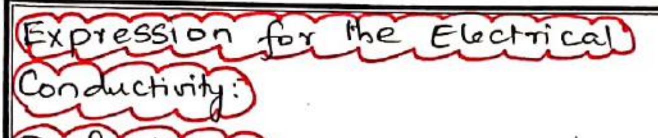
The above equation is used to find the distance between the orgin & the plane, In case of two planes ON = d_1, OP = d_2

Then Inter planar distance

$$\boxed{d = d_2 - d_1}$$

Downloaded from EnggTree.com

EnggTree.com



Expression for the Electrical Conductivity:

Definition:-

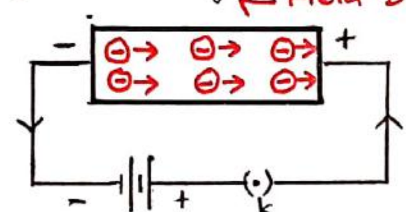
It is the quantity of Electrical charges flowing per unit time (t) per unit area (A) maintained at a unit potential gradient (E).

$$\sigma = \frac{Q}{tAE} = \frac{ne^2\tau}{m^*} \quad \Omega^{-1}m^{-1}$$

Derivation:

When an electrical field applied to an electron of charge 'e', It moves in a opposite direction with the applied field with a constant velocity (v_d) known as "drift velocity"

← Field Direction



Here the force experienced by the electron by external field

$$F = eE \quad \text{—} (1)$$

and the acceleration gained by the electron 'a' is given by

$$\text{acceleration } a = \frac{\text{velocity}}{\text{Time}} = \frac{v_d}{\tau}$$

$$\therefore a = \frac{v_d}{\tau}$$

$$v_d = a\tau \quad \text{—} (2)$$

We know that from Newton's II law

$$F = ma \quad \text{—} (3)$$

By comparing eqns (1) & (3)

$$eE = ma$$

$$a = \frac{eE}{m} \quad \text{—} (4)$$

Substituting eqn (4) in eqn (2)

$$v_d = \frac{eE\tau}{m} \quad \text{—} (5)$$

If $n \rightarrow$ no. of free electron
$e \rightarrow$ charge of an electron

Then current density interms of 'v_d' is given by

$$J = nev_d \quad \text{—} (6)$$

Substitute eqn (5) in eqn (6)

$$J = ne\frac{eE\tau}{m}$$

$$J = \frac{ne^2E\tau}{m} \quad \text{—} (7)$$

From the definition of Charge density is directly proportional to applied electric field.

$$J \propto E$$

$$J = \sigma E \quad \text{—} (8)$$

Comparing eqns (7) & (8) we get

$$\sigma E = \frac{ne^2\tau E}{m}$$

$$\sigma = \frac{ne^2\tau}{m} \quad \text{—} (9)$$

Eqn (9) is the expression for the electrical conductivity.

CHENNAI INSTITUTE OF TECHNOLOGY DEPARTMENT OF SCIENCE AND HUMANITIES
Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

Thermal Conductivity:

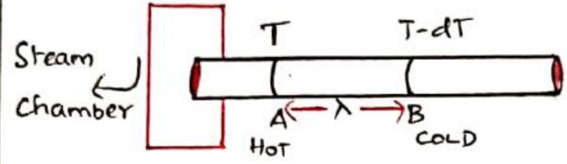
Definition:

It is the amount of heat conducted per unit area (A), per unit time (t) maintained at unit temperature gradient.

$$K = \frac{Q}{dT/dx} = \frac{n v^2 K_B \tau}{2}$$

Derivation:-

Consider a unifor metallic rod contain free electron.



Here A & B → Cross-sectional area near hot & cold end

T, T-dT → Temp at A & B.

λ → Mean free path

The average K.E of electrons crossing A

$$E_1 = \frac{1}{2} m v^2 = \frac{3}{2} K_B T \quad \text{—(1)}$$

III'y K.E of free electron at 'B'

$$E_2 = \frac{3}{2} K_B (T - dT) \quad \text{—(2)}$$

Excess energy carried out by electrons from A to B

$$K.E = \frac{3}{2} K_B T - \frac{3}{2} K_B (T - dT)$$

$$= \frac{3}{2} K_B T - \frac{3}{2} K_B T + \frac{3}{2} K_B dT$$

$$K.E = \frac{3}{2} K_B dT \quad \text{—(3)}$$

Assume, the electron can move in all possible direction, then the no. of electron crossing per unit area, per unit time from 'A' to 'B'.

$$n = \frac{1}{6} n v \quad \text{—(4)}$$

∴ The excess average energy carried from A to B is given by

$$E = \frac{1}{6} n v \times \frac{3}{2} K_B dT$$

$$E = \frac{1}{4} n v K_B dT \quad \text{—(5)}$$

Hence the net amount of heat transformed from 'A' to 'B'.

$$Q = \frac{1}{4} n v K_B dT - \left[-\frac{1}{4} n v K_B dT\right]$$

$$Q = \frac{1}{2} n v K_B dT \quad \text{—(6)}$$

from the definition, we know that

$$Q = K \cdot \frac{dT}{dx}$$

$$Q = K \cdot \frac{dT}{\lambda} \quad \text{—(7)}$$

By comparing eqn (7) & (6)

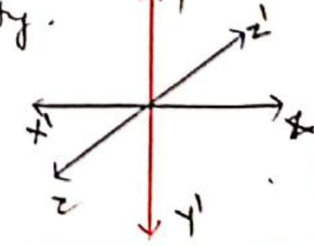
$$K \frac{dT}{\lambda} = \frac{1}{2} n v K_B dT$$

$$K = \frac{1}{2} n v K_B \lambda \quad \text{—(8)}$$

wkt $\lambda = \tau v$

$$\therefore \boxed{K = \frac{1}{2} n v^2 K_B \tau} \quad \text{—(9)}$$

Eqn (9) is the expression for thermal conductivity.



CHENNAI INSTITUTE OF TECHNOLOGY DEPARTMENT OF SCIENCE AND HUMANITIES

Downloaded from EnggTree.com

Scanned with CamScanner

EnggTree.com

Fermi Distribution function:-

Definition:

It is the probability of occupation of electrons among different energy levels at absolute temperature.

It is given by

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

Where E → Energy level to be considered.

E_F → Fermi energy level.

k_B → Boltzmann Constant

T → Absolute Temperature.

If F(E)=1, the energy level is occupied by an electron.

If F(E)=0, the energy level is vaccant

If F(E) = 0.5, then there is 50% chance for the electron to occupy.

Case (i)

If $E < E_f$ at T=0K

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

$$= \frac{1}{1+e^{(E-E_F)/0}}$$

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

$$F(E) = 1$$

Thus at T=0K, 100% chance for the electrons to occupy the energy levels.

Case (ii)

If T=0K at $E > E_F$

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

$$= \frac{1}{1+e^{\infty}} = \frac{1}{1+\infty}$$

$$F(E) = 0$$

Thus 0% chance for the electron to occupy the energy levels.

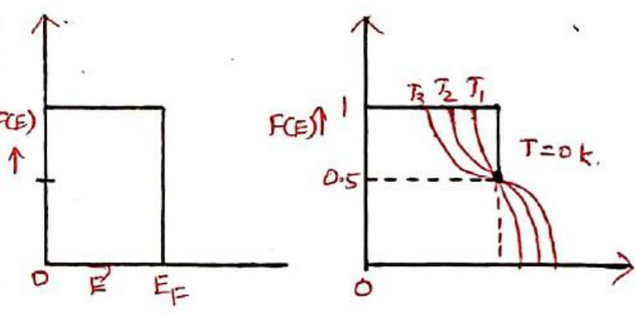
Case (iii)

If T>0K at $E = E_F$

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

$$F(E) = \frac{1}{2} \quad \text{or} \quad F(E) = 0.5$$

There is 50% chance for the electrons to occupy the fermi energy level



Variation of E_F with respect to temperature.

When T=0K, occupation is upto E_F

When T>0K valence electrons got breakdown in its bond and exited to conduction band.

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

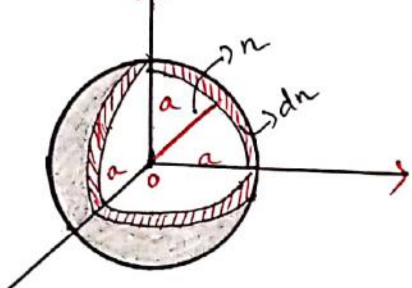
Density of Energy States:-

Definition:

It is defined as the no. of available energy states presented per unit volume of a metal piece.

$$Z(E)dE = \frac{N(E)dE}{V}$$

$$\text{Density of Energy states} = \frac{\text{No. of available energy state between E \& E+dE}}{\text{Volume of a metal.}}$$



Let us consider a sphere inside a cubical metal piece of side 'a'.

* Here n_x, n_y, n_z are the coordinate axes.
* $n \rightarrow$ inner radius of the sphere.
* E and E+dE are the energy of the inner and outer shell of the sphere.
* The sphere consists of no. of shells, between inner and outer shell each represents a energy level.

The no of available energy states within the thickness of the sphere of radius 'n'

$$n = \frac{1}{8}\left[\frac{4\pi n^3}{3}\right] \quad \text{—(1)}$$

III'ly the energy states within the sphere of radius (n+dn)

$$n+dn = \frac{1}{8}\left[\frac{4}{3}\pi(n+dn)^3\right] \quad \text{—(2)}$$

Hence, the no. of avaliable energy states between (n & n+dn) the energy interval E and E+dE.

$$N(E)dE = \frac{1}{8}\left[\frac{4}{3}\pi(n+dn)^3 - \frac{4}{3}\pi n^3\right]$$

$$= \frac{1}{8}\left[\frac{4}{3}\pi(n^3 + 3n^2dn + 3ndn^2 + dn^3 - n^3)\right]$$

$$N(E)dE = \frac{1}{8}\left[\frac{4}{3}\pi(3n^2dn + 3ndn^2 + dn^3)\right]$$

$\because$ dn very small, neglecting the higher orders,

$$N(E)dE = \frac{1}{8}\left[\frac{4}{3}\pi(3n^2dn)\right]$$

$$N(E)dE = \frac{\pi}{2}n^2dn \quad \text{—(3)}$$

We know that the energy of an electron in a cubical metal piece of side 'a' is

$$E = \frac{n^2h^2}{8ma^2} \quad \text{—(4)}$$

Differentiating eqn (4) we have

$$dE = \frac{2n\,dn \cdot h^2}{8ma^2}$$

(ie) $$n\,dn = \frac{8ma^2}{2h^2} \cdot dE \quad \text{—(5)}$$

From eqn (4)

$$n^2 = \frac{8ma^2}{h^2}E$$

$$n = \left[\frac{8ma^2E}{h^2}\right]^{1/2} \quad \text{—(6)}$$

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

Hence eqn ③ can be written as

$$N(E)dE = \frac{\pi}{2} n \cdot n dn \quad \text{—} ⑦$$

By substituting eqn ⑤ & ⑥ in ⑦

$$N(E)dE = \frac{\pi}{2}\left[\frac{(8m)^{1/2} a E^{1/2}}{h}\right]\left[\frac{8ma^2 dE}{2h^2}\right]$$

$$\therefore N(E)dE = \frac{\pi}{2}\frac{(8m)^{3/2} a^3 E^{1/2} dE}{2h^3} \quad \text{—} ⑧$$

Here $a^3 = V \rightarrow$ volume

$\therefore$ Density of energy states

$$Z(E)dE = \frac{N(E)dE}{V}$$

$$Z(E)dE = \frac{\pi (8m)^{3/2} V E^{1/2} dE}{4h^3 \cdot V}$$

$$Z(E)dE = \frac{\pi}{4h^3}(8m)^{3/2} E^{1/2} dE \quad \text{—} ⑨$$

According to Pauli's exclusion principle in each state 2 electrons can be accomodated.

$$\therefore Z(E)dE = 2 \times N(E)dE$$

$$\therefore Z(E)dE = 2 \times \frac{\pi}{4h^3}(8m)^{3/2} E^{1/2} dE$$

$$Z(E)dE = \frac{\pi}{2h^3}(8m)^{3/2} E^{1/2} dE \quad \text{—} ⑩$$

Carrier Concentration in Metals:

The no. of electrons per unit volume in a given energy interval is calculated by

$$n_c = \int Z(E) F(E) dE \quad \text{—} ⑪$$

We know that

$$Z(E)dE = \frac{\pi}{2h^3}(8m)^{3/2} E^{1/2} dE$$

$$= \frac{\pi}{2h^3}(8)^{3/2}(m)^{3/2} E^{1/2} dE$$

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

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

$$Z(E)dE = \frac{4\pi}{h^3}(2m)^{3/2} \cdot E^{1/2} dE \quad \text{—} ⑫$$

$F(E) = 1$ for energy levels $E = 0$ to $E = E_{F_0}$

Then eqn ⑪ becomes

$$n_c = \frac{4\pi}{h^3}(2m)^{3/2}\int_0^{E_{F_0}} E^{1/2} dE$$

$$n_c = \frac{4\pi}{h^3}(2m)^{3/2}\left[\frac{E^{3/2}}{3/2}\right]_0^{E_{F_0}}$$

$$= \frac{4\pi}{h^3}(2m)^{3/2} \cdot \frac{2}{3}\left[E_{F_0}\right]^{3/2}$$

$$n_c = \frac{8\pi}{3h^3}(2mE_{F_0})^{3/2} \quad \text{—} ⑬$$

Fermi Energy:-

From eqn ⑬, we know that the carrier concentration n_c can be written as

$$n_c = \frac{8\pi}{3h^3}(2m)^{3/2}(E_{F_0})^{3/2}$$

$$\frac{3n_c}{8\pi}\frac{h^3}{(2m)^{3/2}} = \left[E_{F_0}\right]^{3/2}$$

By raising power on bothsides by 2/3

$$E_{F_0} = \left[\frac{3n_c}{8\pi}\frac{h^3}{(2m)^{3/2}}\right]^{2/3}$$

$$E_{F_0} = \left[\frac{3n_c}{8\pi}\right]^{2/3}\left[\frac{h^2}{2m}\right] \quad \text{—} ⑭$$

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

Effective Mass of Electron:-

Definition:-

The mass acquired by an electron, when it is accelerated in a periodic potential is called effective mass (m^*)

Derivation:-

Consider a crystal subjected to electric field (E). Then the velocity gained by the electrons (v). It is described by the wave vector (k) & it is equivalent to the wave packet moving with a group velocity (v_g).

$$v_g = \frac{d\omega}{dk} \quad \text{--- (1)}$$

where $\omega \rightarrow$ angular velocity ($2\pi\nu$)

$k \rightarrow$ wave vector.

We know that

$E = h\nu$ (or) $\omega = 2\pi\nu$

$\nu = \frac{\omega}{2\pi}$

$$E = \frac{h\omega}{2\pi}$$

$$E = \hbar\omega \qquad \hbar = \frac{h}{2\pi}$$

$$\omega = \frac{E}{\hbar} \quad \text{--- (2)}$$

$\therefore$ Eqn (1) can be written as

$$v_g = \frac{d}{dk}\left[\frac{E}{\hbar}\right]$$

$$v_g = \frac{1}{\hbar}\left[\frac{dE}{dk}\right] \quad \text{--- (3)}$$

Under this condition the acceleration 'a' of an electron

$$a = \frac{dv_g}{dt}$$

$$= \frac{d}{dt}\left[\frac{1}{\hbar}\left(\frac{dE}{dk}\right)\right]$$

$$a = \frac{1}{\hbar}\frac{d^2E}{dk^2} \cdot \frac{dk}{dt} \quad \text{--- (4)}$$

The momentum of an electron from de-Broglie wave length

$$p = \frac{h}{\lambda}$$

$$p = \frac{h}{2\pi} \cdot \frac{2\pi}{\lambda}$$

$$p = \hbar \frac{2\pi}{\lambda}$$

$$p = \hbar k \quad \text{--- (5)}$$

Differentiate eqn (5) w.r.t. 't'

$$\frac{dp}{dt} = \hbar\frac{dk}{dt} \quad \text{(or)} \quad \frac{dk}{dt} = \frac{F}{\hbar} \quad \text{--- (6)}$$

[Force acting on the electron $F = \frac{dp}{dt}$]

Hence eqn (4) can be written as

$$a = \frac{1}{\hbar} \cdot \frac{d^2E}{dk^2} \cdot \frac{F}{\hbar}$$

$$a = \frac{F}{\hbar^2}\frac{d^2E}{dk^2}$$

$$F = \left[\frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)}\right] a \quad \text{--- (7)}$$

When an electric field is applied, acceleration of the electron due to field.

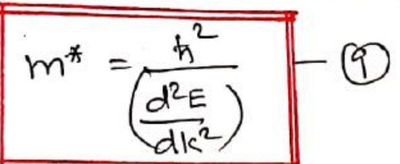
$$a = \frac{eE}{m^*} = \frac{F}{m^*}$$

$$F = m^* a \quad \text{--- (8)}$$

Comparing eqns (7) & (8)

$$m^* a = \left[\frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)}\right] a$$

Downloaded from EnggTree.com
Scanned with CamScanner



$$m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)} \quad \text{--- (9)}$$

Eqn (9) → Effective mass of an electron is not constant, but depends on the value $\frac{d^2E}{dk^2}$

Case(i): $\frac{d^2E}{dk^2} = +ve$, $m^* = +ve$

Case (ii) $\frac{d^2E}{dk^2} = -ve$, $m^* = -ve$

Case (iii) $\frac{d^2E}{dk^2} \rightarrow$ more, m^* is ~~higher~~ lesser

Case (iii) $\frac{d^2E}{dk^2} \rightarrow$ less m^* is ~~less~~ large

Tight Binding Approximation:-

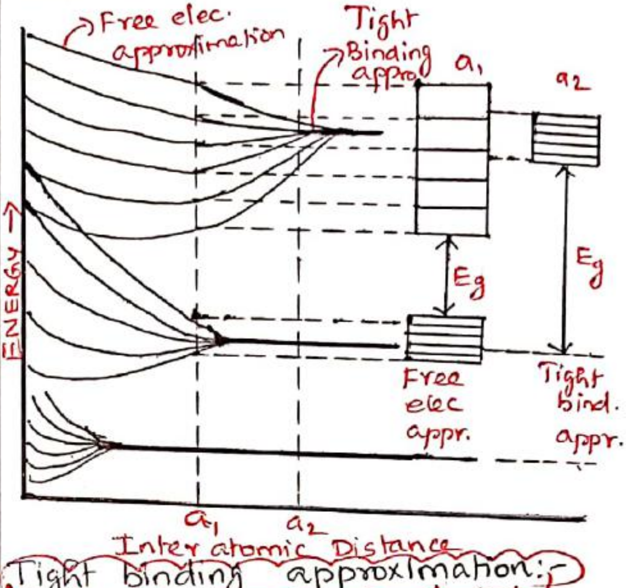
Before discussing about the tight binding approximation, let us know about free electron approximation.

Free electron approximation:-

In solids, ionic core which are tightly bounded to lattice location exists. The electrons are free to move throughout the solid. This is called the free electron approximation.

In free electron approximation,

* The P.E of the e^- is assumed to be lesser than its total energy.
* The width of the band gap (E_g) are smaller than the allowed band. (fig)
* The interaction between the neighbouring atoms will be very strong.
* As the atoms are closer to each other, the inter atomic distance decreases and hence the wave functions overlap with each other.



Tight binding approximation:-

Instead of beginning with the solid core, we begin with the electrons, (ie) all the electrons are bounded to the atoms. In otherwords, atoms are free while the electrons are tightly bounded. This is called tight bound approximation.

In tight binding approximation:

* The P.E of the electrons is nearly equal to the total energy
* The width of the forbidden bands (E_g) are larger than the allowed bands.
* Therefore the interactions between the neighbouring atom will be weak.
* As the atoms are not closer, the interatomic distance increases and hence the wave functions will not overlap.

CHENNAI INSTITUTE OF TECHNOLOGY DEPARTMENT OF SCIENCE AND HUMANITIES
Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

Dia, Para, Ferro Magnetic Effects.

Dia	Para	Ferro
(i) It is non-magnetic material consits of no-permanent dipoles	Temporary magnetic material. consits of permanent dipole.	Permanent magnetic material. consits of large no. of permanent dipoles.
(ii) Dipoles are opposite to each other in the absence of external field. Net dipole moment is zero	Dipoles are randomly oriented in the absence of external field. Net dipole moment is minimum.	Dipole are oriented parallel to each other, in the absence of external field. net dipole moment is large.
(iii) In the presence of external field dipole allign opposite to the external field.	In the presence of external field dipoles allign parallel to the external field.	Here also, dipoles allign parallel to the external field.
(iv) Magnetic flux lines are repelled out of the material.	Magnetic flux lines are attracted by the material	Magnetic flux lines are attracted maximum by the material.
(v) Bin << Bout	Bin >> Bout	Bin >>> Bout
(v) Permiability (μ) is less than 1 and susceptibility is -ve $\mu << 1$, $\chi = -ve$	Permiability (μ) is greater than 1 & susceptibility is +ve. $\mu > 1$, $\chi = +ve$	Permiability (μ) is very much greater than 1, susceptibility is +ve, $\mu >> 1$, $\chi = +ve$
(vi) Independent on temperature	Dependent on temperature	Dependent on temperature
(vii) At very low temp. it will be in diamagnetic	Temp above maximum para mag. converted into Dia mag. is known as curie Temp.	Above curie temperature it is converted in to para materials
Ex: Bismuth, Gold,	Ex: Al, Pt.	Ex: Fe, Ni, Co.

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

Paramagnetism in the Conduction Electrons in metals

According to Langevin's theory the paramagnetic susceptibility is inversely proportional to the temperature.

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

But in some metals susceptibility is independent of temperature.

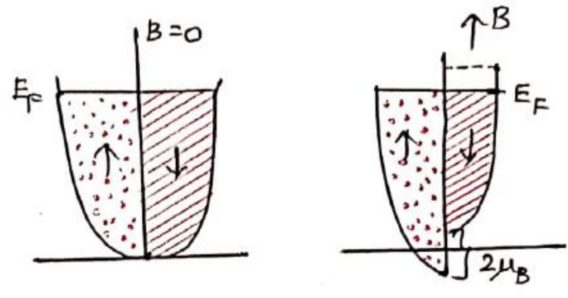
Pauli explains that it is due to the free electrons, can orient only in two directions, either along the magnetic field or against it.

Consider a curve between density of states versus energy at absolute zero of temperature. In this curve there are two parts, one have electron spin along z-direction and another have electron spin opposite to z direction.

In the absence of external field the distribution of electrons in the two parts are equal.

∴, Net mag. moment of the electron gas is zero.

When a mag. field (B) is applied along z-direction, the energy of the spins aligned parallel to B is lowered by the amount μ_B while the energy of the spins opposite to B is raised by the same amount.



As a result, the Fermi level of the two spin distribution shift with respect to each other and energetically unstable situation.

In order to acquire stable configurations, the e's lying near the Fermi level with antiparallel spins flip into the region of parallel spins until the two Fermi levels become equal again.

No. of electrons which change their direction

$$N_{eff} = \frac{1}{2} Z(E_F) \mu_B B$$

where $Z(E_F) \rightarrow$ Density of states

$\mu_B \rightarrow$ mag. moment of electron.

The factor $1/2$ is due to the fact that the density of states of one spin distribution is half of the total density of the states.

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

∴ After application of the field

No. of electrons with spin parallel > No. of electron with spin anti-parallel.

Since each flip increases the magnetisation by $2\mu_B$ (from $-\mu_B$ to $+\mu_B$), the net magnetisation is given by

$$M \approx N_{eff} \times 2\mu_B = Z(E_f)\mu_B^2 B \quad \text{—(2)}$$

The Pauli spin susceptibility of the electron is

$$\chi_p = \mu_0 \mu_B^2 Z(E_f) \quad \text{—(3)}$$

$B = \mu_0 H$, $\chi_p = \frac{M}{H}$

From eqn, we know that χ_p is independent of temp.

From FD distribution we obtain

$$Z(E_F) = \frac{3N}{2E_F}$$

$N \rightarrow$ no. elec per unit volume

$$\therefore (3) \Rightarrow \chi_p = \frac{3\mu_0 N \mu_B^2}{2E_F} = \frac{3\mu_0 N \mu_B^2}{2kT_F}$$

Where $E_F = kT_F$

$$\chi_p = \frac{3}{2}\chi\frac{T}{T_F}$$

Where $\chi = \frac{\mu_0 N \mu_B^2}{kT}$ Classical susceptibility

Since T_F is normally very high, χ_p is smaller than χ by about two orders of magnitude, which is in agreement with experimental results.

Exchange Interaction:

The Weiss theory of ferro-magnetism explains about the molecular field but it is not possible to explain large value of internal field.

To explain the large internal field, Heisenberg gave an explanation which is based on the non magnetic interaction called exchange interaction between electron.

These force appears in the form of spin-spin interaction and strength of the interaction depends upon the interatomic separation. If the interatomic distance is decreased, the electron spin are decreased and the exchange force decreases and become anti parallel spins.

According to Heisenberg theory, the change interaction between electrons in different quantum states lead to a lower energy provided the spin quantum number of the both states are parallel.

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

∴ The exchange interaction between the electrons is given by

$$E_{ex} = -2 J_{ij} S_i S_j$$

Where J_{ij} → The exchange integral for the two atoms.

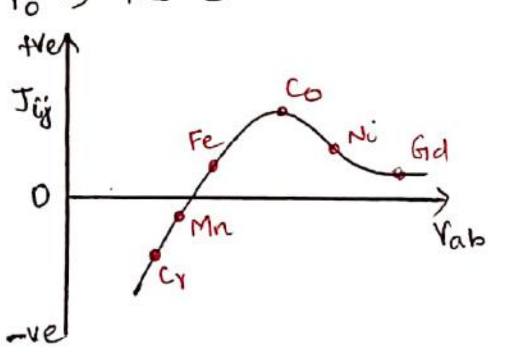
S_i → spin angular moments associated with i^{th} state.

S_j → spin angular moments associated with j^{th} state.

A plot of exchange integral value (J_{ij}) and the interatomic distance (r_{ab})

r_{ab} → interatomic distance.

r_0 → the orbital radius of electron



From graph,

1. The value of J_{ij} is +ve when $\frac{r_{ab}}{r_0} > 3$ (ie) the exchange energy is -ve and hence the parallel orientation is high. Due to this atom possess ferromagnetic properties [Ex: Fe, Co, Ni, Gd]

2. The value of J_{ij} is -ve when $\frac{r_{ab}}{r_0} < 0$ (ie) the exchange energy is +ve and hence the atoms coming under this criteria possess anti-ferromagnetic properties [Ex: Cr, Mn]

SQUID

SQUID stands for Superconducting Quantum Interference Device. It is an ultrasensitive instrument used to measure very weak magnetic field of the order of 10^{-14} tesla.

Principle:

We know that a small change in magnetic field produces variation in the quantum flux.

Description and Working

→ Magnetic field
Superconductor
→ Josephson Junction)
I
Biasing Current
→ Josephson Junction - 2
V

A SQUID consists of a superconducting ring which can have magnetic fields of quantum values (1, 2, 3 ...) of flux placed in between two Josephson junctions as shown in figure.

When the magnetic field is applied perpendicular to the plane of the ring, the current is induced at the two Josephson junctions. The induced current produces the interference pattern and it flows arround the ring

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

So that the magnetic flux in the ring can have the quantum value of magnetic field applied.

Application:

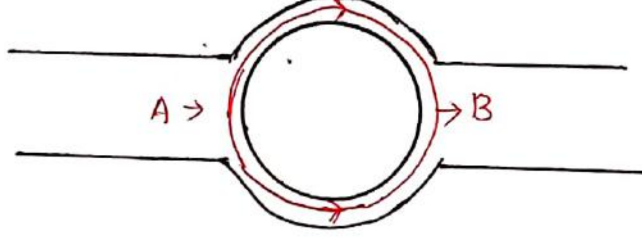
(i) SQUID can be used to detect the variation of very minute magnetic signals in terms of quantum flux.

(ii) It can also be used as storage device for magnetic flux.

(iii) SQUID is useful in the study of earthquakes, removing para-magnetic impurities, detection of magnetic signals from the brain, heart etc.

Quantum Interference Transistor:

Electrons are made to propagate through two arms of the quantum wire ring as shown in the figure.



Suppose an electron wave enters the rings from left to right. The wave entering through 'A' gets split up into two partial waves. A constructive interference can be expected to occur at "B" similar to the optical anlogue as they travel through the same distance.

The constructive interference at the output of the device reduces the resistance of the ring. Various methods of introducing a phase difference of π between the two waves have been sugested. This leads to destructive interference which in turn will increase the resistance by reducing the current.

An external voltage can control the nature of interference and the current. This device is expected to act as a high speed transistor.

GMR Devices - Magnetic Hard Disk Drive with GMR Sensor:

GMR sensors, which has a very high magnetic sensitivity are used to read the data at greater speed.

Principle:

In Hard Disk drives, the binary data in terms of zero's (0) and one's (1) are stored by inducing.

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

magnetic moment in a thin mag- layer and GMR effect is used as the principle to read the data in HDD.

Here zero(0) represents missing transition and one(1) represents transition in the medium.

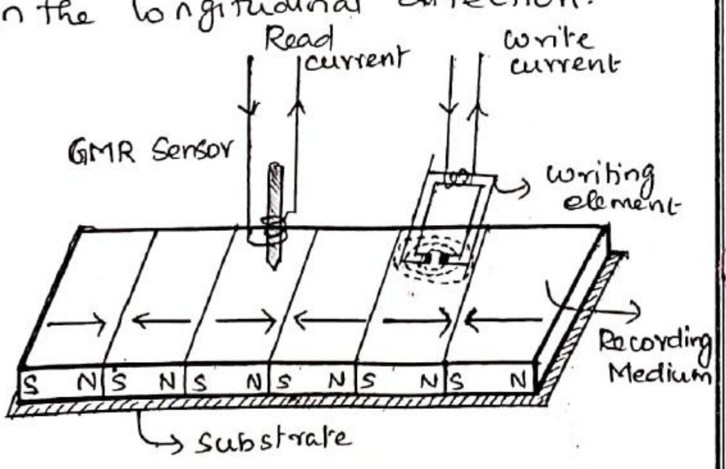
Construction:-

* The HDD consists of recording medium made up of thin layer of magnetic garnets grown over the substrate the GMR sensor.

* The substrate is made up of ferrites and anti ferromagnetic materials. This is used as reading element

* The writing element is made up of inductive magnetic transducer.

* The writing element and the GMR sensor shall be made to slide over the recording media in the longitudinal direction.



Working:- (Writing)

1. Initially the current is passed through the writing element and a magnetic field is induced in between the gap of the inductive magnetic transducer.

2. During writing, the amplitude of current is kept constant, and the direction of current is reversed.

3. Due to reversal of current the reversal of current, the magnetization orientation is reversed in the recording medium (i.e) from south → North.

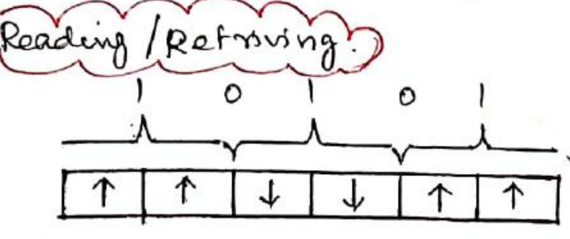
4. When the induced magnetic field is greater than the Coercivity of the recording media, then data is recorded in the form of 1.

5. Thus one(1) is stored as data in the recording medium as a magnetic transition.

6. When there is no magnetic transition, then it is referred as zero.

7. In this way 0's & 1's are stored in the recording medium

Reading / Retriving:



Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com

1. GMR effect is the principle used to read/retrieve the data
2. When GMR sensor is moving near the recorded medium, then the resistance of GMR sensor varies with respect to orientation of the magnetic moments. as follows.

* When the layer are magnetised in parallel manner then the resistance is minimum, therefore maximum current flows. This is represents the data as One (1)

* When the layers are magnetised in antiparallel manner, then the resistance is maximum, therefore minimum (no current) current flows. This is represents the data as Zero (0)

3. Therefore, with the help of the reading current, the zero's (0's) and one's (1's) can be retrieved from the magnetic hard disc.

Advantages:

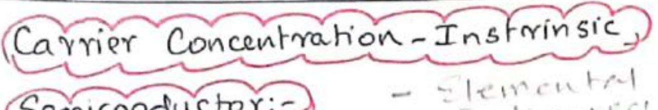
* Very large storage capacity.
* Compact in size.
* Non diffusive & very sensitive in reading.

Disadvantages:

* HDD is slower than SSD
* Consume more power
* Data may be corrupted, due to thermal radiation.

Downloaded from EnggTree.com
Scanned with CamScanner

EnggTree.com



Carrier Concentration - Intrinsic Semiconductor:-

- Elemental
- Indirect

The no. of charge carriers per unit volume of the material is called carrier concentration also known as density of charge carriers.

Derivation:

In intrinsic semi conductor the no. of electrons in the conduction band (n) and holes in the valence band (p) is equal to each other at T>0K.

$$n = p = n_i$$

The density of electrons in the conduction band (n) is given by

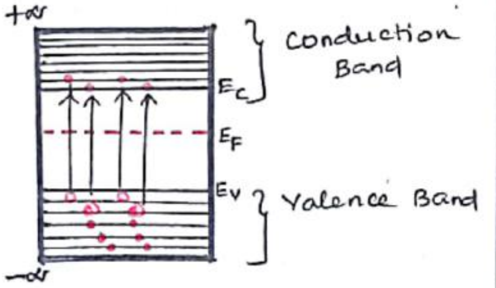
$$\int dn = n = \int_{E_c}^{\infty} Z(E)\,F(E)\,dE \quad \text{---(1)}$$

We know that, Density of energy states

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

Probability of Electron occupation

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



$$\therefore n = \int_{E_c}^{+\infty} \frac{4\pi}{h^3}(2m_e^*)^{3/2} E^{1/2} \frac{1}{1+e^{\frac{(E-E_f)}{k_BT}}}\,dE \quad \text{---(4)}$$

Here

m_e^* - Effective mass of Electron.

E - KE of conduction electron

$$E = E - E_c$$

E_c - Lower conduction Energy level.

Eqn (4) can be written

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \int_{E_c}^{+\infty} \frac{(E-E_c)^{1/2}}{1+e^{\left(\frac{E-E_f}{k_BT}\right)}}\,dE \quad \text{---(5)}$$

We know that at T>0K

$$E - E_f >> k_BT$$

$$\frac{E-E_f}{k_BT} >> 1 \quad (or) \quad e^{\left(\frac{E-E_f}{k_BT}\right)} >> 1$$

$$\therefore 1 + e^{\frac{(E-E_f)}{k_BT}} \simeq e^{\frac{(E-E_f)}{k_BT}}$$

Hence eqn (5) can be written as

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \int_{E_c}^{\infty} \frac{(E-E_c)^{1/2}}{e^{\left(\frac{E-E_f}{k_BT}\right)}}\,dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \int_{E_c} (E-E_c)^{1/2} e^{E_f - E/k_BT}\,dE$$

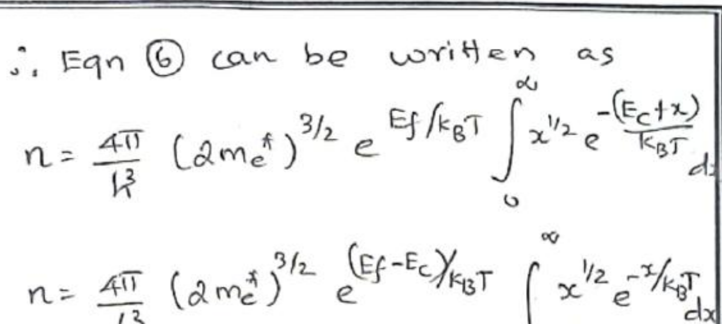
$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{E_f/k_BT} \int_{E_c} (E-E_c)^{1/2} e^{-E/k_BT}\,dE \quad \text{---(6)}$$

To calculate eqn (6)

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

Downloaded from EnggTree.com

∴ Eqn ⑥ can be written as



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

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{(E_f-E_c)/k_BT} \int_0^\infty x^{1/2} e^{-x/k_BT} dx$$

Using gamma function

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

Hence

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{(E_f-E_c)/k_BT} \frac{\sqrt{\pi}}{2}(k_BT)^{3/2}$$

$$n = 2\left[\frac{2\pi m_e^* k_BT}{h^2}\right]^{3/2} e^{\frac{(E_f-E_c)}{k_BT}} \quad \text{— (8)}$$

Eqn ⑧ is the expression for the density of electrons in a Conduction band.

Density of Holes (P) :-

It is given by

$$\int_{E_1}^{E_2} dP = P = \int_{E_1}^{E_2} Z(E)\, dE\, [1 - F(E)] \quad \text{— (9)}$$

Here

$$Z(E)\, dE = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{1/2} dE$$

here

$$m = m_h^*$$

$$E = E_v - E.$$

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

By substituting and simplyfying the density of holes

$$P = 2\left[\frac{2\pi m_h^* k_BT}{h^2}\right] e^{\frac{(E_v-E_f)}{k_BT}} \quad \text{— (10)}$$

Expression for intrinsic carrier concentration.

As we know in intrinsic Semiconductor at any temperature above $T > 0K$

$$n = p = n_i \quad \text{— (11)}$$

$$n \times p = n_i \times n_i = n_i^2$$

Hence

$$n_i^2 = n \times p \quad \text{given by} \quad \text{— (12)}$$

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

$$n_i^2 = 4\left[\frac{2\pi k_BT}{h^2}\right]^3 (m_e^* m_h^*)^{3/2} e^{\frac{(E_v-E_c)}{k_BT}}$$

$$n_i = 2\left[\frac{2\pi k_BT}{h^2}\right]^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2k_BT} \quad \text{— (13)}$$

Eqn ⑬ is the expression for the carrier concentration of intrinsic Semiconductor.

Density of Holes :-

It is given by

$$\int_{E_1}^{E_2} dp = P = \int_{E_1}^{E_2} Z(E)\, dE \cdot [1 - F(E)]$$

Downloaded from EnggTree.com

EnggTree.com

Here

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

Here $m = m_h^*$

$$E = E_v - E$$

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

Eqn ①

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

$$P = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{-E_f/k_BT} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{E/k_BT}\, dE \quad \text{—②}$$

Let

	when	when
$E_v - E = x$	$E = -\infty$	$E = E_v$
$E = E_v - x$	$E_v - (-\infty) = x$	$E_v - E_v = x$
$dE = -dx$	$E_v + \infty = x$	$x = 0$
	$x = \infty$	

Eqn ② becomes

$$P = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{(-E_f/k_BT)} \int_{\infty}^{0} x^{1/2} e^{\frac{(E_v - x)}{k_BT}} (-dx)$$

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

Using Gamma function

$$\int_0^{\infty} x^{1/2} e^{-x/k_BT}\, dx = \frac{\sqrt{\pi}}{2}[k_BT]^{3/2}$$

Hence

$$P = \frac{4\pi}{h^3}[2m_h^*]^{3/2} e^{\frac{E_v - E_f}{k_BT}} \frac{\pi^{1/2}}{2}(k_BT)^{3/2}$$

$$\boxed{P = 2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2} e^{\frac{(E_v - E_f)}{k_BT}}}$$

The above equation is the expression for the density of holes in the valence Band.

Extrinsic Semi Conductor

Def:

Impure Semiconductors are the one in which charge carriers generated by adding impure atoms to the pure semiconductors.

Types:

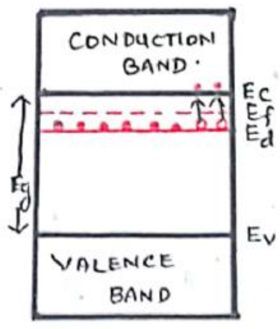
These are classified into two types based on the type of impurity types

(i) n type (penta valent impurity)

(ii) p type (Trivalent impurity)

Carrier Concentration - n type Semiconductor

* The energy level diagram is shown in the figure.



* The energy level of excess electron is called donor energy level (E_d). This is located above valence band.

Downloaded from EnggTree.com

EnggTree.com

WKT the density of electrons in the conduction band

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

m_e^* → Effective mass

k_B → Boltzmann Constant

No. of holes (or) donors = $N_d [1 - F(E_d)]$ --- (2)

$F(E_d)$ – Probability of Electron in donar energy level.

$1 - F(E_d)$ – Probability of ionized donars

N_d – Total no. of donar atoms per unit volume.

$$\therefore F(E_d) = \frac{1}{1 + e^{\left(\frac{E_d - E_f}{k_B T}\right)}}$$

∴ Eqn (2)

$$= N_d \left[1 - \frac{1}{1 + e^{\frac{E_d - E_f}{k_B T}}}\right]$$

$$= N_d \left[\frac{1 + e^{(E_d - E_f)/k_B T} - 1}{1 + e^{(E_d - E_f)/k_B T}}\right]$$

$$= N_d \frac{e^{(E_d - E_f)/k_B T}}{1 + e^{(E_d - E_f)/k_B T}}$$

$E_d < E_f$ therefore $E_d - E_f$ −ve

$$\therefore 1 + e^{(E_d - E_f)/k_B T} \simeq 1$$

∴ The above eqn can be written as

The density of ionised donors (or) holes $\}$ $n_h = N_d e^{(E_d - E_f)/k_B T}$

At equilibrium

Density of Electron in the conduction Band (n) = Density of holes in the Donor energy level (n_h)

$\therefore n = n_h$

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

By Rearranging the above eqn

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

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

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

Taking log on bothsides,

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

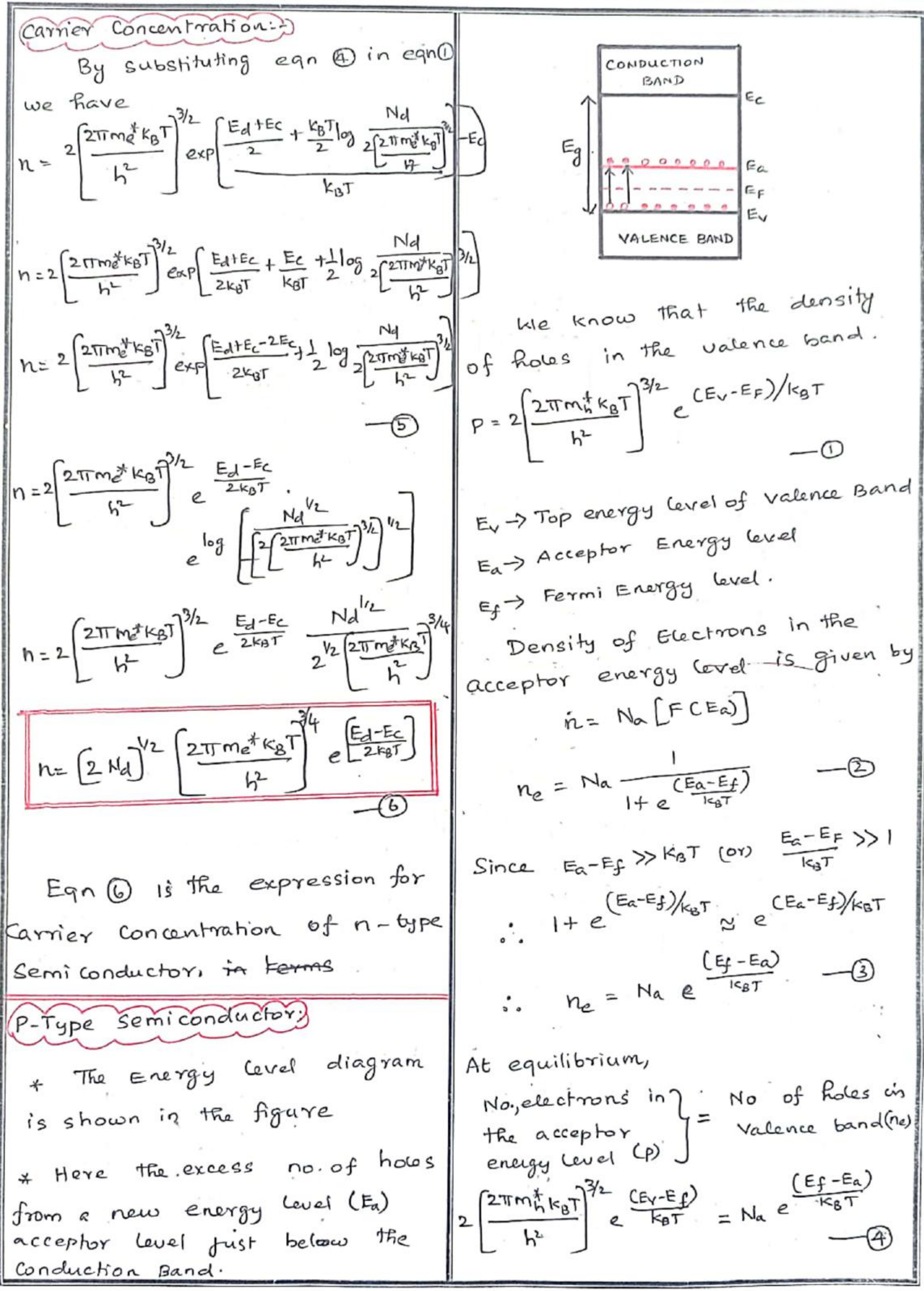
$$2E_f - (E_c + E_d) = k_B T \log\left[\frac{N_d}{2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2}}\right]$$

$$2E_f = E_c + E_d + k_B T \log\left[\frac{N_d}{2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2}}\right]$$

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

Downloaded from EnggTree.com

EnggTree.com



Carrier Concentration:-

By substituting eqn (4) in eqn (1) we have

$$n = 2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2} \exp\left[\frac{\frac{E_d+E_c}{2} + \frac{k_BT}{2}\log \frac{N_d}{2\left[\frac{2\pi m_e^* k_BT}{h^2}\right]^{3/2}} - E_c}{k_BT}\right]$$

$$n = 2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2} \exp\left[\frac{E_d+E_c}{2k_BT} + \frac{E_c}{k_BT} + \frac{1}{2}\log \frac{N_d}{2\left[\frac{2\pi m_e^* k_BT}{h^2}\right]^{3/2}}\right]$$

$$n = 2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2} \exp\left[\frac{E_d+E_c-2E_c}{2k_BT} + \frac{1}{2}\log \frac{N_d}{2\left[\frac{2\pi m_e^* k_BT}{h^2}\right]^{3/2}}\right] \quad \text{--- (5)}$$

$$n = 2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2} e^{\frac{E_d-E_c}{2k_BT}} \cdot e^{\log\left[\frac{N_d^{1/2}}{\left[2\left[\frac{2\pi m_e^* k_BT}{h^2}\right]^{3/2}\right]^{1/2}}\right]}$$

$$n = 2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2} e^{\frac{E_d-E_c}{2k_BT}} \frac{N_d^{1/2}}{2^{1/2}\left[\frac{2\pi m_e^* k_BT}{h^2}\right]^{3/4}}$$

$$n = (2N_d)^{1/2}\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/4} e^{\left[\frac{E_d-E_c}{2k_BT}\right]} \quad \text{--- (6)}$$

Eqn (6) is the expression for carrier concentration of n-type semiconductor.

P-Type semiconductor:

* The Energy level diagram is shown in the figure
* Here the excess no. of holes from a new energy level (E_a) acceptor level just below the conduction band.

CONDUCTION BAND, E_c, E_g, E_a, E_F, E_v, VALENCE BAND

We know that the density of holes in the valence band.

$$p = 2\left[\frac{2\pi m_h^* k_B T}{h^2}\right]^{3/2} e^{(E_v-E_F)/k_BT} \quad \text{--- (1)}$$

$E_v \rightarrow$ Top energy level of valence Band

$E_a \rightarrow$ Acceptor Energy level

$E_f \rightarrow$ Fermi Energy level.

Density of Electrons in the acceptor energy level is given by

$$n = N_a[F(E_a)]$$

$$n_e = N_a \frac{1}{1+e^{\frac{(E_a-E_f)}{k_BT}}} \quad \text{--- (2)}$$

Since $E_a - E_f \gg k_BT$ (or) $\frac{E_a-E_F}{k_BT} \gg 1$

$$\therefore 1 + e^{(E_a-E_f)/k_BT} \simeq e^{(E_a-E_f)/k_BT}$$

$$\therefore n_e = N_a e^{\frac{(E_f-E_a)}{k_BT}} \quad \text{--- (3)}$$

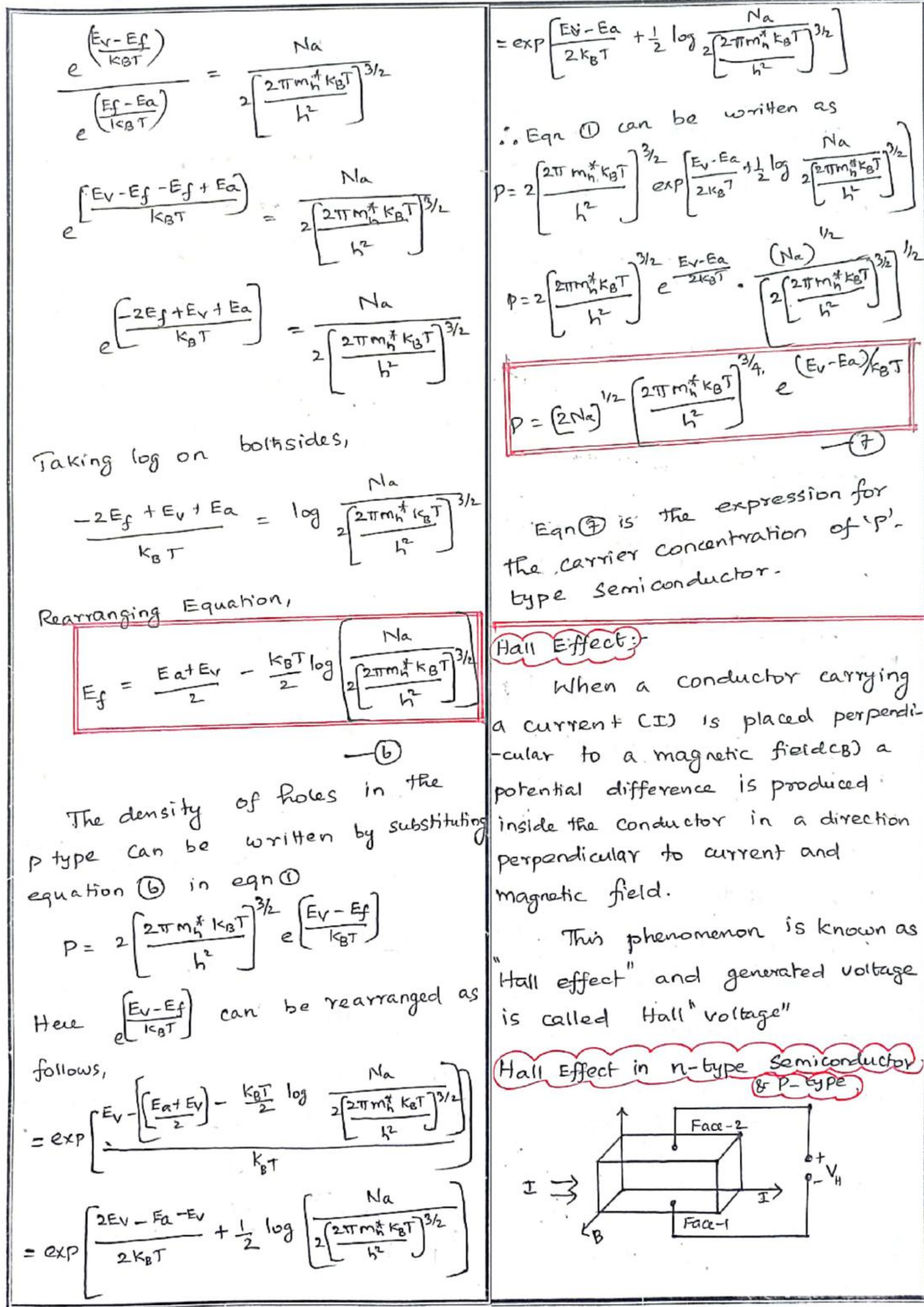
At equilibrium,

No. electrons in the acceptor energy level (p) = No of holes in valence band (n_e)

$$2\left[\frac{2\pi m_h^* k_B T}{h^2}\right]^{3/2} e^{\frac{(E_v-E_f)}{k_BT}} = N_a e^{\frac{(E_f-E_a)}{k_BT}} \quad \text{--- (4)}$$

Downloaded from EnggTree.com

EnggTree.com



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

$$e^{\left[\frac{E_v-E_f-E_f+E_a}{k_BT}\right]} = \frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}$$

$$e^{\left[\frac{-2E_f+E_v+E_a}{k_BT}\right]} = \frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}$$

Taking log on bothsides,

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

Rearranging Equation,

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

The density of holes in the p type can be written by substituting equation (6) in eqn (1)

$$P = 2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2} e^{\left[\frac{E_v-E_f}{k_BT}\right]}$$

Here $e^{\left[\frac{E_v-E_f}{k_BT}\right]}$ can be rearranged as follows,

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

$$= \exp\left[\frac{2E_v - E_a - E_v}{2k_BT} + \frac{1}{2}\log\left[\frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}\right]\right]$$

$$= \exp\left[\frac{E_v-E_a}{2k_BT} + \frac{1}{2}\log\frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}\right]$$

∴ Eqn (1) can be written as

$$p = 2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}\exp\left[\frac{E_v-E_a}{2k_BT} + \frac{1}{2}\log\frac{N_a}{2\left[\frac{2\pi m_h^* k_BT}{h^2}\right]^{3/2}}\right]$$

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

$$p = (2N_a)^{1/2}\left(\frac{2\pi m_h^* k_BT}{h^2}\right)^{3/4} e^{(E_v-E_a)/k_BT} \quad \text{--- (7)}$$

Eqn (7) is the expression for the carrier concentration of 'p'-type semiconductor.

Hall Effect:-

When a conductor carrying a current (I) is placed perpendicular to a magnetic field (B) a potential difference is produced inside the conductor in a direction perpendicular to current and magnetic field.

This phenomenon is known as "Hall effect" and generated voltage is called "Hall voltage".

Hall Effect in n-type Semiconductor & P-type

Downloaded from EnggTree.com

EnggTree.com

Consider n-type semiconductor in the form of rectangular slab. Current (I) flow in x-direction magnetic field (B) is applied in z-direction, Due to Hall effect Voltage devolped along y-direction (in fig). current flow due to electron flow.

Electrons moving with velocity 'v', experience downward force.

Force due to magnetic field (Downward) } $= Bev$ —(1)

Force due to potential difference } $= eE_H$ —(2)

At equilibrium (1) = (2)

$Bev = eE_H$

$E_H = Bv$ —(3)

Face-2 (+ + + + +), I →, (− − − − −) Face-1

we know that

current density

$J_x = -nev$

$v = \frac{-J_x}{ne}$ —(4)

Substitute eqn (4) in eqn (3)

$E_H = B\left(\frac{-J_x}{ne}\right)$

$E_H = R_H J_x B$ —(5) where $R_H = \frac{-1}{ne}$

−ve sign indicates Elec field in −ve Y axis

∴ Hall coefficient

$$R_H = \frac{E_H}{J_x B}$$

III'ly in P-type semiconductor Current flow due to flow of holes (+ve charge)

Compare with n-type semiconductor current density $J_x = pev$

$v = \frac{J_x}{pe}$ —(6)

Substitute eqn (6) in (3)

$E_H = R_H J_x B$ —(7)

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

Face-2 (− − − −), (+ + + + +) Face-1

Hall coefficient interms of Hall voltage

Hall voltage $V_H = E_H t$ —(8)

where $E_H \rightarrow$ Hall field.

Substitute eqn (7) in eqn (8).

$V_H = R_H J_x B t$ —(9)

Area of the sample A = thickness × Breadth

$A = bt$

current density $J_x = \frac{I_x}{A}$

$J_x = \frac{I_x}{bt}$ —(10)

Substitute eqn (10) in eqn (9)

$V_H = \frac{R_H I_x B t}{bt}$

$V_H = \frac{R_H I_x B}{b}$ —(11)

$$R_H = \frac{V_H b}{R_H B} \quad \text{—(12)}$$

Eqn (12) gives hall coefficient in interms of hall voltage.

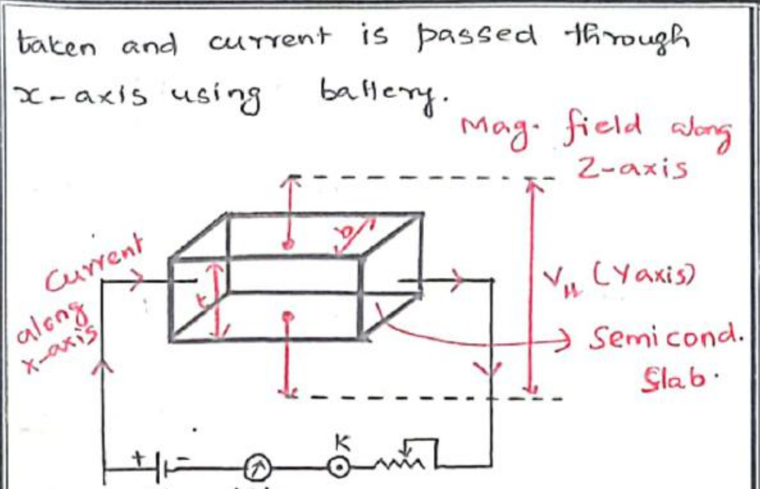
Experimental Determination of Hall Coefficient

A semiconductor slab of thickness 't' and breadth 'b' is

Downloaded from EnggTree.com

EnggTree.com

taken and current is passed through x-axis using battery.



The slab is placed between poles of an electromagnet. Magnetic field is applied along Z-axis. The Hall Voltage (V_H) is measured by placing two probes at the centre of the top and bottom of the slab.

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

$$R_H = \frac{V_H b}{I_x B}$$

Mobility of charge Carriers:

We know that, Hall coefficient

$$R_H = -\frac{1}{ne}$$

The above expression is valid only for conductors, where the velocity is taken as drift velocity.

For n-type semiconductor

$$R_H = \frac{-1.18}{ne}$$

$$ne = \frac{-1.18}{R_H} \quad \text{--- (1)}$$

For p-type semi conductor

$$R_H = \frac{1.18}{pe} \qquad pe = \frac{1.18}{R_H} \quad \text{--- (2)}$$

Electrical conductivity

for n-type semiconductor

$$\sigma_e = n e \mu_e \quad \text{--- (3)}$$

$$(1) \Rightarrow \mu_e = \frac{\sigma_e}{\frac{-1.18}{R_H}}$$

$$\mu_e = \frac{-\sigma_e R_H}{1.18} \quad \text{--- (4)}$$

For p-type semicond.

$$\sigma_h = p e \mu_h \quad \text{--- (5)}$$

$$(2) \Rightarrow \mu_h = \frac{\sigma_h}{\frac{1.18}{R_H}}$$

$$\mu_h = \frac{\sigma_h R_H}{1.18} \quad \text{--- (6)}$$

Application of Hall Effect:-

(i) Used to determine whether the material is p-type or n-type semiconductor.

(ii) Used to find the carrier concentration

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

(iii) used to find the mobility of charge carriers

$$\mu_e = \sigma_e R_H \quad , \quad \mu_h = \sigma_h R_H$$

Schottky Diode:-

Schottky diode is a unilateral device, in which current flow from metal to semiconductor in one direction.

+ [Schottky diode symbol] -

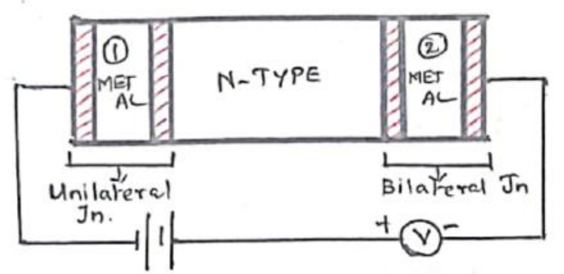
Construction:

A Schottky diode also called as Schottky barrier diode. It is made up of 2 junctions.

Downloaded from EnggTree.com

EnggTree.com

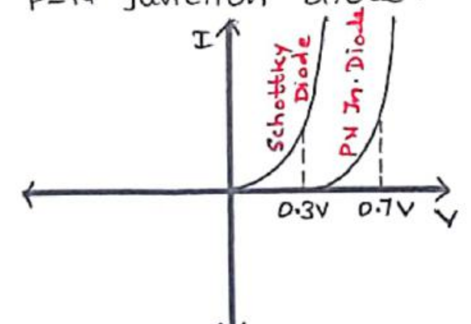
(i) Unilateral [Metal-Semiconductor]
(ii) Bilateral [Metal-Semiconductor]



The Schottky diode act as a terminal device in which metal 1 and Semiconductor formed at one end act as anode with unilateral junction, metal 2 and Semi conductor formed at other end act as cathode with bilateral junction.

Working:

Applying forward bias, the voltage applied to diode and their corresponding current is measured. The V-I curve is drawn for Schottky diode as compared with P-N Junction diode.



As per V-I curve, during forward bias for a Schottky diode I increase enormosly even for small applied V, due to 3 components of current occurs in schottky diode

Application:

* Due to low voltage drop, they are used in high switching system
* They are used in BJT
* It is used is Radio frequency application.
* It is used in high power supply

Ohmic Contacts:

Definition:

An ohmic contact is a type of metal semiconductor junction. It is formed by a contact of a metal with a heavily doped semiconductor.

When the Semiconductor has a higher work function than that of metal, then the junction formed is called the ohmic junction.

Here the current is conducted equally in both directions.

Accumulation Region
Bulk Semi cond.
ϕ_m ϕ_m CB E_C E_F E_{F_n} E_V VB
Metal Semi cond — Before Contact
Metal n-type — After Contact

CHENNAI INSTITUTE OF TECHNOLOGY — DEPARTMENT OF SCIENCE AND HUMANITIES

Downloaded from EnggTree.com

EnggTree.com

Working:

Fermi levels of the metal and Semiconductor are at different positions before contact. [Fig (i)]

After contact, at equilibrium the electrons move from the metal to the empty states in the conduction band of Semiconductor.

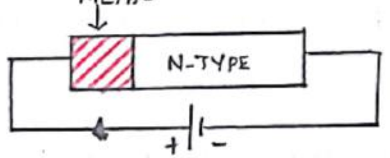
∴ An accumulation region near the interface is appeared. (Semi-conductor side)

Fermi levels after contact are shown in [fig(ii)].

Accumulation region has a higher conductivity than the bulk semiconductor due to higher concentration.

Ohmic contact behaves as a resistor conducting in both forward and reverse biase. (Fig. iii).

The resitivity is determined by the bulk resistivity of the semiconductor.



V-I characteristics:

I
Negligible Yoltage drop
ohmic Contact
O
V

The current density is propertional to the potential across the junction.

Ohmic contacts are non-rectifying and show negligible voltage drop and resistance irrespective of the direction and magnitude of current.

Applications:

The use of ohmic contact is to connect one semiconductor device to another, an IC or to connect an IC to its external terminals

Downloaded from EnggTree.com

EnggTree.com

OPTO ELECTRONICS DEVICE - LIGHT DECTORS:

* Opto electronic devices such as light dectors (or) photo dectors are the devices which convert the light signal into electrical signals.

* The Three main photo detectors used in optical fiber communication system are

(i) P-i-n - Photo diode (PIN Diode)
(ii) Avalanche Photo diode (APD)
(iii) PN junction photo dector

→ P-i-n - Photo Diode (PIN Diode)

* Principle:

- This Diode works in Reverse bias. Under reverse bias, light is made to fall on neutral region.
- Electron hole pairs are generated and accelerated by the external electric field, which results in photo-current.

* Construction:

- It consists of three region P, i and n.
- The p-n regions are madeup of semiconductor material [silicon, germanium].
- The intrinsic region is a neutral, where it is at the centre of the p-type and n-type region and it is lightly doped with n-material.
- Since the p-n region is seperated by an intrinsic region (i), it is called as positive - intrinsic - negative (P-i-n) photo diode.

photon
p^+ | (i) | n^+
Intrinsic region
R_L V_{out}

Working:

* The PIN Diode is given very high reverse bias to attract the charge carriers from the intrinsic region.

* The photon incident on the intrinsic region produces electron-hole pair, by the transfer of electrons from Valence band to Conduction band, leaving a hole.

* The movement of electrons in the conduction band creates flow of charges. Hence light energy is converted into electrical energy.

CHENNAI INSTITUTE OF TECHNOLOGY DEPARTMENT OF SCIENCE AND HUMANITIES
Downloaded from EnggTree.com

EnggTree.com

Solar Cell:

*** Principle:**

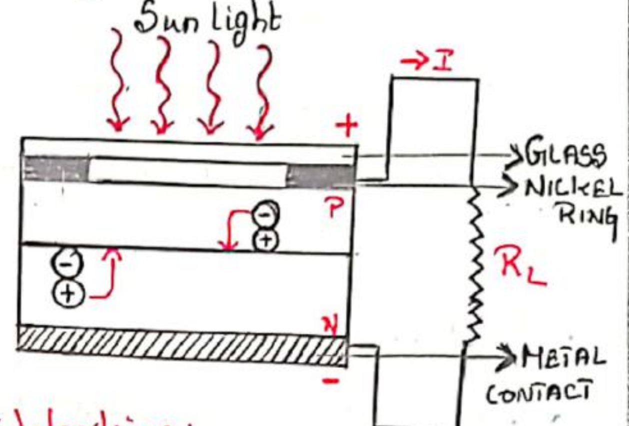
A solar cell is basically a P-N junction photo diode, which converts solar energy (light energy) into electrical energy. With larger efficiency of photon absorption.

* The symbol of the solar cell

Anode — P — n — cathode.

*** Construction:**

- A solar cell is made up of a heavily doped 'p' and "n" type material.
- The P-N diode is packed in a can with glass window on top such that light may fall upon P and N type material.
- The thickness of the p-region and n-region is very small. Therefore charge carriers generated in this region can easily diffuse to the junction.
- Nickel ring at the top and metal at bottom act as terminals.
- The two terminals connected to the load resistance R_L through the ohmic contacts.

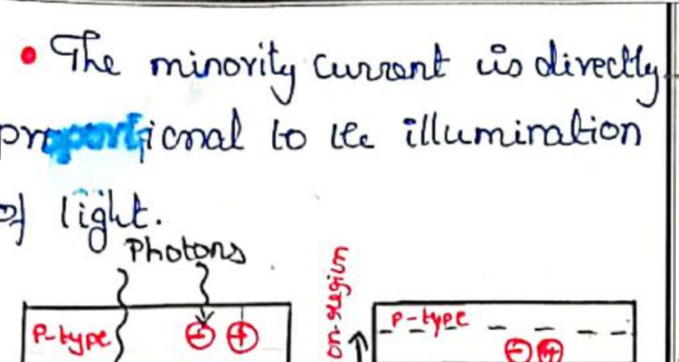


*** Working:**

- Light radiation is allowed to fall on P-N junction diode, without load resistence (R_L).
- The photon energy is sufficient to break the covalent bond and produce electron-hole pair.
- There electrons and holes quickly diffuses and reaches the depletion region.
- Therefore the strong barrier electric field existing in the junction
- The minority carrier electrons in the p-side cross the barrier potential to reach N-side and the holes in N-side move to the p-side.

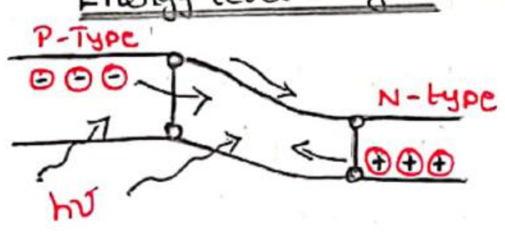
CHENNAI INSTITUTE OF TECHNOLOGY — DEPARTMENT OF SCIENCE AND HUMANITIES
Downloaded from EnggTree.com

- The minority current is directly proportional to the illumination of light.



- The electrons and holes accumulate on either side of the junction, which gives rise to open-circuit voltage (V_o).
- Load Resistance R_L is connected across the diode, reverse current I_R flows through the circuit.

Energy level Diagram



* Merits:
  - utilize renewable energy.
  - Eco-friendly
  - pollution free
  - Life time durability high.

* Demerits:
  - Cost is very high.
  - Seasonal energy
  - Occupies more energy.

* Uses:
  - power production.
  - used in artifical satellite and space probes.

LIGHT EMITTING DIODE (LED).

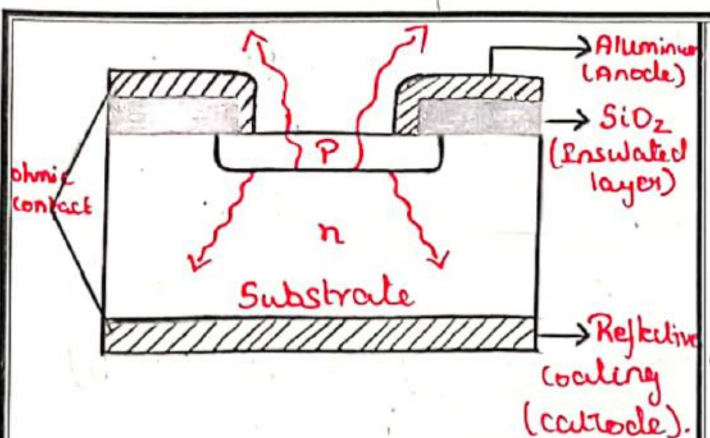
* Definition:
  - LED is a semiconductor P-n junction diode which converts electrical energy to light energy under forward biasing.

Symbol.

* Principle:
  - Injection luminescence is the principle used in LED's.
  - The injection of electrons into the p-region from n-region makes a direct transition from conduction band to valence band. The electrons recombines with holes and emits photons of energy Eg

* Construction:
  - The p-n junction is formed by diffusion techniques by doping silicon with GaAS crystal.
  - Where, n-type is grown on a substrate and a p-type layer is deposited on it by diffusion.

Downloaded from EnggTree.com



- To increase the radiative recombination, the thickness of n-layer is higher than the thickness of 'P' layer.
- Ohmic contacts are made by aluminium in such a way that top layer "p" material is left uncovered for the emission of light, where the carrier recombination takes place.

* Working:

- Under forward biasing, Majority charge carriers of n-type (electrons) moves to p-type as minority carriers
- Similarly, majority charge carriers of p-type (holes) moves to n-type as minority carriers
- By this process, excess of minority carriers are injected in both p and n region. This is called minority carrier injection.
- Biasing voltage is further increased, excess minority charge carriers diffuse away from the junction and directly recombine with the majority carriers.
- Therefore electron-hole recombination process occurs, thereby photon is emitted.

Energy level diagram:

* Merits:

- Very fast Response.
- Cost is very low.
- Smaller in size.
- Long life time.

* Demerits:

- power output is low
- Less Directional.
- Intensity is lesser than Laser.

* Applications:

- Used in display devices.
- Used in pilot light.
- Used in indicator lamp.
- IR LEDS used in wire-less communication.

Downloaded from EnggTree.com

LASER DIODE:

* Definition:

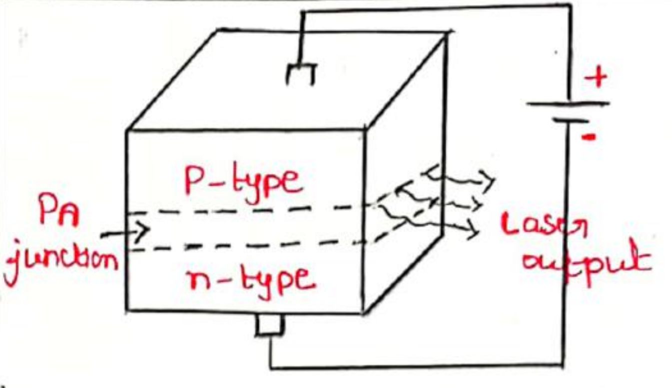
It is a specially fabricated P-n junction diode. This diode emits Laser light when it is forward-biased.

* Principle:

Recombination of electron-hole pair leads to emission of light in forward biasing known as recombination radiation.

* Construction:

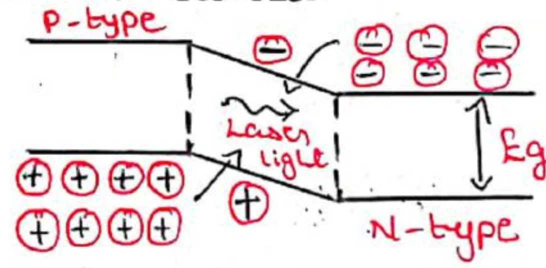
- The active medium is a P-n junction diode made from a single crystal of GaAs.
- The Crystal is cut in the form of platelet (0.5mm-thickness) Consists of two regions n-type & p-type.
- Metal electrodes are connected to both upper & lower surfaces of the S.C diode.
- Forward bias voltage is applied through metal electrodes.



- The photon emission is stimulated in a very thin layer of pn junction.
- The end faces of the Pn junction are well polished and parallel to each other.
- It acts as an optical resonator through which the emitted light comes out.

* Working:

- When the pn-junction is forward biased.



- Electrons & holes are injected into junction region.
- The region around junction contains a large number of electrons in the conduction band and holes in Valence band

Downloaded from EnggTree.com

- During recombination, light photons are produced.
- During Forward bias Voltage is increased, more photons are emitted.
- These photons trigger a chain of stimulated recombinations more photons in phase travel forth & back by two polished surfaces of junction.
- After gaining enough strength Laser beam of wavelength 8400 Å is emitted from the junction. $E_g = hc/\lambda$.

* Merits:
  - Compact in size.
  - High efficiency..
  - Less power Consumption.
  - Waveform is Continuous/pulsed.

* Demerits:
  - Output has large divergence
  - poor coherence & Mono-chromaticity

* Applications of Laser diodes:
  - Used in optical communication.
  - Used in Barcode readers.
  - Used in printing industry.
  - Used as writing head in Disc drives.
  - Used in Various Industry applications such as cladding welding etc.

OLED - Organic LED:

* Definition:
  - OLED are solid state devices made up of thin films of organic molecules that produce light with the application of electricity
  - It is also known as Light emitting polymers (LEP) or Organic electro luminescence
  - Thickness of these layers is around 100 - 500 nm thick.

* Principle:

An electron moves from the cathode to the emissive layer

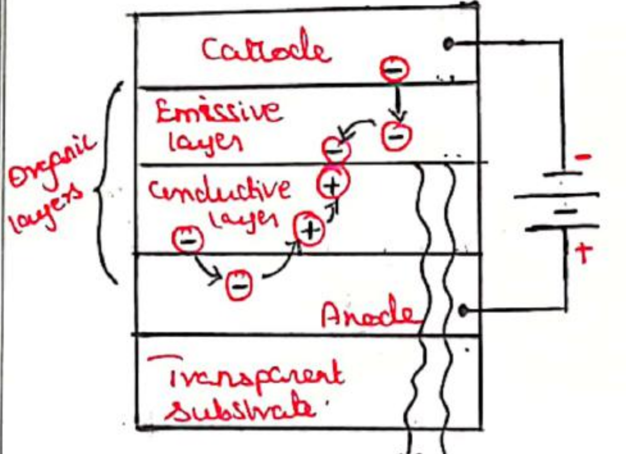
Downloaded from EnggTree.com

EnggTree.com

and hole moves from the anode to the conductive layer and they recombine to produce photons.

* Construction:

- It is constructed with different layers of polymers coated with Organic compound.



- It consist of an emissive layer made up of poly-fluorine and a conductive layer made up of poly-aniline kept between cathode and anode substrate.
- This whole layers placed over transparent electrode layers.

* Working:

- Forward bias voltage is applied across the OLED
- Due to this cathode diffuse electron into emissive layer.
- Anode gets an electron from conductive layer & produces a hole in conductive layer.
- Thus, emissive layer becomes rich in negative charged particles & conductive layer becomes rich in positive charged particles.
- Due to the electrostatic force, electrons and holes, come closer & recombine with each other.
- In organic sc, holes move faster than electrons.
- This recombination produces light and it is emitted through the transparent substrate.

Downloaded from EnggTree.com

* Merits:

- It is thin & flexible.
- Light weight
- Larger field view
- Emission is brighter than normal light (LED'S).

* Demerits:

- Manufacturing cost is high.
- Easily damaged.
- Maintainence is high.

* Application:

- Used in cell phones, car radios, digital camera.
- Used in TV screens, computers displays, advertising
- Automative dash boards.
- Used in flexible display boards.

Downloaded from EnggTree.com

ELECTRO-OPTIC MODULATORS :-

* Electro-Optic Effect:

The phenomenon in which the optical properties of a material change in response to a varying electrical field is known as electro-optic effect and the crystals with special optical properties that allow an electrical signal to control and modulate a beam of light are known as Electro-optic modulators.

Types of electro-optic modulators

Base on type of the modulated beam, electro-optic modulators are classified as

* Intensity modulator.
* phase modulator
* Amplitude modulator
* Polarization modulator.

* Principle:

Electro-optic modulators consists of a non-linear crystal [lithium niobate]. The refractive index varies with strength of the applied electric field. Based on the linear electro-optic effect.

* Operation:

* A voltage applied across the electro-optic crystal.

* Due to plane-polarized light propagating through the crystal to resolved into two components.
* The change in retardation between two components is proportional to the magnitude of the electric field.
* A crossed polarizer analyzes the output beam, resulting in intensity modulation.

* Significance:

* Modify the properties of a travelling light wave.

* Application:

* Communications.
* Information processing.
* Digital signal processing.

CHENNAI INSTITUTE OF TECHNOLOGY DEPARTMENT OF SCIENCE AND HUMANITIES

Downloaded from EnggTree.com

EnggTree.com

* Properties of electro-optic material:
  - Large change in refractive index per volt.
  - High optical quality and transmission.
  - Low dielectric constant.

PLASMONICS:

* Plasmon:

Plasmon is a collective wave where billions of electrons oscillate in synchronization.

* Plasmonics:

Plasmonics refers to the resonant interaction between electromagnetic radiation and free electrons at the interface between a metal and a dielectric material.

* Principle:

Surface Plasmon Resonance

High intense photons and free electron interaction causes generation of density electron waves called surface plasmons.

* Conduction electrons on the nanoparticle surface of the plasmonic material undergo a collective oscillation when excited by light at specific wavelengths.

* This oscillation, which is known as surface plasmon resonance (SPR).

* Theory:

* The plasmon resonance of the free electrons in the metal nanoparticle, studied by polarizability.

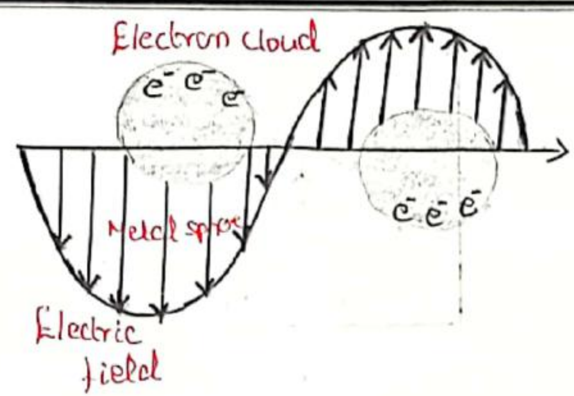
* When an excitation occurs, the electrons will oscillate by external electric field.

* On metal's surface, electrons will make each other to oscillate. After excitation waves will appear [longitudinal or damping]

* Surface plasmons polaritons resonance, controlled by size.

Downloaded from EnggTree.com

EnggTree.com



and optical properties of nano-particle composition and medium in which the particles are embedded.

* Application:

* Superfast optical computers
* Tumor killing cancer therapies
* Laser for self-driving cars.

Switching Devices

The opto-electronic switching devices are very useful for computing and light activated logic gates applications.

* Definition:

Switching refers to a phenomenon in which transmission of an optical field through a device is switched among two or more possible states by optical means.

* Types of Optical switching:

There are two types of optical switching.

* P-i-n [Multi Quantum Well]
  - Self electro optic effect (SEED) device.

* The Quantum Controlled Stark Effect [QCSE]

* Self Electro Optic Effect: [SEED]

* Principle:

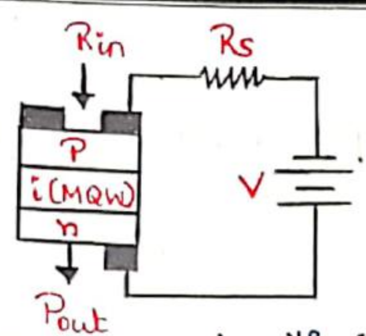
The photocurrent flowing through the current including series resistor, changes the voltage across the modulator, this influences its absorption and transmission.

* Circuit:

* In p-i(MQW)-n diode, by the reverse bias voltage, the tunneling current varies.

* The photocurrent-bias voltage exhibits Negative differential resistance (NDR).

Downloaded from EnggTree.com



* SEED circuit with series resistor
* Pin → incident optical power

$P_{out} = I^2 R_S$ is electric output power.

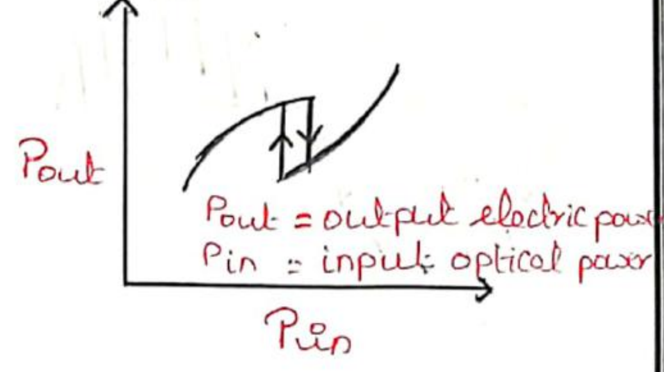
* I is the photo current flowing through resistance (R_S)

* Operation
* The photo current increases due to recombination of electrons and holes [tunneling of charge carriers]

* The negative bias across the diode decreases. The heavy hole absorption peak is shifted to higher energies.

* Voltage drops $I^2 R_S$ across the series resistor increases.

* When the photo current decreases and correspondingly output electric power decreased.



* Increase of input optical power increases the output electric power due to ordinary photon absorption by the diode.

* Photonic switching can also illustrated with two beams, one for transmission and one for control.

Downloaded from EnggTree.com

EnggTree.com

QUANTUM CONFINEMENT:-

It is a process of reducing the size of a bulk solid, so that the energy levels inside become discrete.

The quantum confinment effect is observed when the size of the particle is too small to be comparable to the wavelength of the electron.

In which only small percent of electrons free to move during confinement.

By bottom up (or) top down process the dimensions reduced.

QUANTUM STRUCTURES:-

When a bulk material is reduced in its size, atleast the structure is in the order of few nanometers, then the structure is known as "Quantum structure."

In which the motion of the electrons/holes are confined in one (or) more directions by potential barrier, it is called quantum confined structure.

It is classified into three types based on direction.

1) Quantum well
2) Quantum wire
3) Quantum dot.

1) Quantum well (2-dimension)

If one dimension is reduced to the nanometer range while the other two dimensions remain large, then we get a structure known as "Quantum well".

Construction:

It is made from alternative layers of different semiconductors or by deposition of very thin metal films.

Few nm

Explanation:

It is a larger structure in which the carrier particles are free to move in two dimensions. The particles are confined in one dimension.

Due to confinement of carriers, the quantum well structure are very much useful

Downloaded from EnggTree.com

EnggTree.com

in the production of semiconductor lasers.

2) Quantum wire (1 dimension)

In this two dimensions are reduced and one remains large, the resulting structure is Quantum wire.

It is a one dimensional object. This is known as "quantum wire".

In this charge carriers free to move along one direction. Nanowires and carbontubes are example.

3) Quantum Dots (0-Dimension)

When all the three dimensions are minimized the resulting structure is known as Quantum dot.

In this electrons are restricted to move in any direction, completely confined.

It is a zero dimensional object.

Though a quantum dots has many atoms it is consider more like a single atom due to confinement. It can be used in quantum dot laser, quantum computer & display devices.

Comparison of structures:

Density of states in Quantum well, Quantum wire and Quantum Dot structure:

Bulk structure:

The density of state of a bulk material is given by

$$Z(E) = \frac{8\pi\sqrt{2}\, m^{*3/2}}{h^3} (E-E_c)^{1/2}$$

where E_c - bottom of conduction band energy

m^* - effective mass of electron.

Downloaded from EnggTree.com

EnggTree.com

Quantum well structure:

The electrons can move freely in two directions (2D) and confined in only one direction.

$$Z(E) = \frac{4\pi m^*}{h^2} \quad \boxed{E_0 > E_i}$$

$i = 1, 2, 3$

→ Energy

Quantum wire structure:

In which two directions confined.

$$Z(E) = \frac{2\sqrt{2}\, m^* (E - E_i)^{-1/2}}{h} \quad i = 1, 2, 3$$

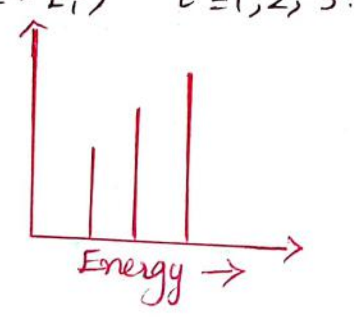
Density of states

Energy →

Quantum dot:-

In this all three directions are confined.

$$Z(E) = \delta(E - E_i) \quad i = 1, 2, 3.$$



Coulomb - Blockade effects:-

The charging effect which blocks the injection or rejection of a single charge into or from a quantum dot is called coulomb blockade effect.

Conditions:

* If more charges near one another. They exert coulomb force.
* If they are same then they repulse each other.

Condition for observing Coulomb blockade effect is

$$W_c = \frac{e^2}{2C} >> k_B T$$

where C - capacitance of the quantum dot.

T - Temperature of the system.

W_c - charging energy needed to add one electron to dot.

Single Electron transistor (SET):

SET is three - terminal switching device which can transfer electrons from source to drain one by one.

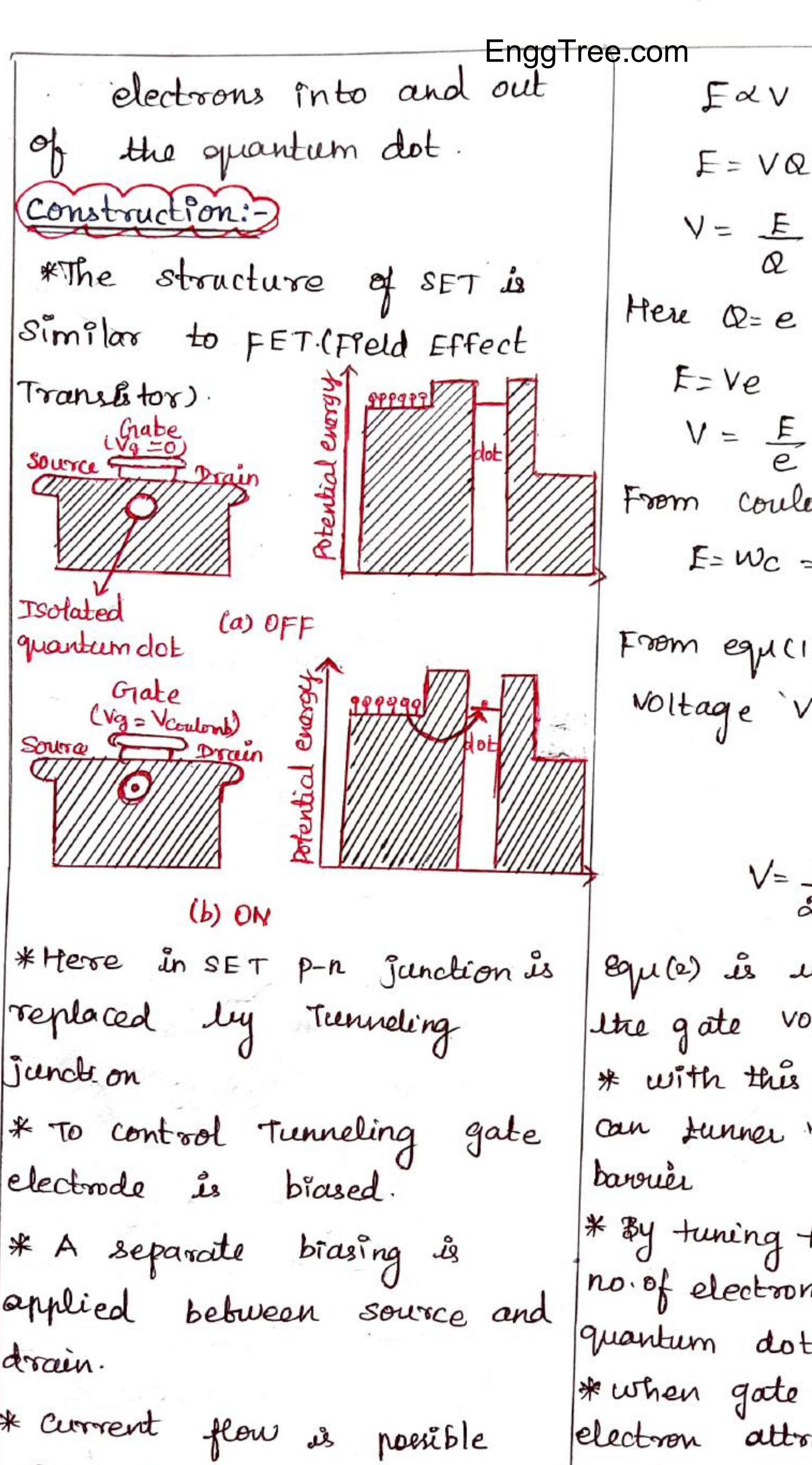
SET is to individually control the tunneling of

Downloaded from EnggTree.com

electrons into and out of the quantum dot.

Construction:-

* The structure of SET is similar to FET (Field Effect Transistor).



* Here in SET p-n junction is replaced by Tunneling junction
* To control Tunneling gate electrode is biased.
* A separate biasing is applied between source and drain.
* Current flow is possible when the gate bias voltage is larger.

The energy needed to move a charge 'Q' is given by

$$E \propto V$$

$$E = VQ$$

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

Here $Q = e$ (- charge of electrons)

$$E = Ve$$

$$V = \frac{E}{e} \quad \text{------ (1)}$$

From coulomb blockade

$$E = W_C = \frac{e^2}{2C}$$

From equ (1)

$$\text{Voltage 'V'} = \frac{E}{e} = \frac{W_C}{e}$$

$$= \frac{e^2/2C}{2}$$

$$V = \frac{e}{2C} \quad \text{------ (2)}$$

equ (2) is used to measure the gate voltage.

* with this potential an electron can tunnel 'coulomb blockade' barrier
* By tuning this voltage the no. of electrons tunneling the quantum dot determined.
* when gate voltage is low electron attracted by the Quantum dot.
* No current flows from source to drain.
* when the gate voltage is raised electron flows from

Downloaded from EnggTree.com

from dot-drain for single electron.

Gate voltage $V_g = V_{coulomb}$

For two electron $V_g = V_c + e/2c$

For three electron $V_g = V_c + e/2c + e/2c$

These on and off states can be used to make an effective switch out of SET.

b) ON

Merits

* Fast information transfer
* No wire is needed between arrays.
* It is suitable for high density memory.
* It can be used for next generation quantum computer.

Demerits

* It is very hard to fabricate
* To operate at room temperature the size of the quantum dot should be small and in the order of 10nm.

Applications:

* It is used in sensor techniques.
* It is used for mass data storage.
* used in highly sensitive electrometers.
* It can be used as temperature probe.
* SET is a suitable measurement set-up for single-electron spectroscopy.

Resonant Tunneling diode:

Resonant tunneling occurs through a potential profile which consists of two potential barriers, so called double barrier structure which are located very close to each other.

Principle:

Resonant tunneling diode works on the principle of tunneling effect, in which the charge carriers cross the energy barriers even with lesser energy than the barrier potential, quantum mechanically. The probability of tunneling increases with the decreasing barrier energy.

Downloaded from EnggTree.com

EnggTree.com

Carbon nano tubes :-

Definition:

Carbon nanotubes are tubes or wires of pure carbon (or) rolled sheets of graphite.

* Hexagonal lattice of carbon is simply "graphite".
* A single layer of graphite is called "graphene"
* CNT consists graphene layers rolled up into a cylindrical shape.

Classification of CNT:-

Based on the layers. CNT's classified as

* single-walled - one layer (SWNT)
* Multi walled - more than one layer coaxially arranged (MWNT).

CNT structures:-

Based on the orientation of rolling three structures obtained.

(i) Arm chair structure:-

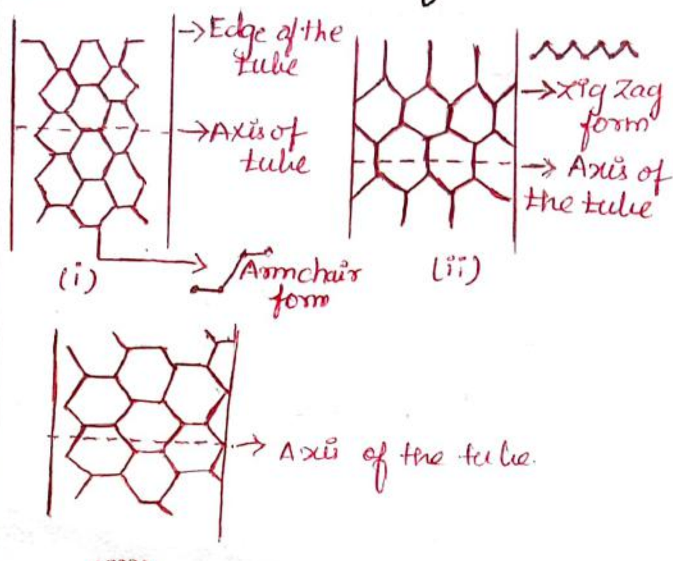
Here axis of the tube parallel to c-c bonding of the hexagons.

(ii) Zig-zag structure:-

Here the axis of the tubes Not parallel (⊥re) to the carbon - carbon bonding.

iii) Chiral form:-

Here c-c bonding is lined towards the axis of the tube.



Properties:

a) Mechanical properties:

* Carbon-carbon bond is a strong bond formation
* Due to this carbon nanotubes have high strength.
* Young's modulus of CNT is 10times greater than steel.
* Tensile strength is relatively high
* It has a ability to withstand extreme strain.

b) Thermal properties:

* CNT's have high thermal conductivity
* It increases with decrease in diameter.

c) chemical properties:

* CNT shows good resistant to chemical reactions

Downloaded from EnggTree.com

EnggTree.com

* It won't get oxidize easily.
* Independent of temperature.

Physical properties:

* Strength-to-weight ratio is high.
* It is 100 times greater than steel and twice that of conventional carbon fibres.

Electrical properties:

* CNT's are metallic (or) semiconductor in nature.
* The energygap of semiconducting CNT's inversly proportional to the diameter.

$$E_g \propto \frac{1}{\text{Diameter}}$$

* Eg minimum at the ends.
* Carbon nanotube treated as "quantum wire" at low temperature.

Applications:

Nanotubes has wide range of applications:

* They are light weight & very strong. Hence used in aerospace.
* Used in constructing nanoscale electronic devices.
* CNT's are use in battery electrodes fuel cells.
* Used as reignforcement element.
* Plastic composites used as a light weight shielding
* Semiconducting CNT's are used as switching devices.
* Used as a chemical gas sensors.
* Used as a catalysts for chemical reactions.
* Used in military and communication devices.
* CNT's are very useful in the production of 'FET'.
* Vaccum tube lamps are produced using carbon nanotubes

Downloaded from EnggTree.com

EnggTree.com

Ballistic Transport

The dimension of conductor is smaller than the mean free path of the electron then the transport of electron is called Ballistic transport

* It is observed in a metal nano wire.

* Conditions of Ballistic Transport:

The mean free path can be increased by reducing the number of impurities in a crystal.

Conditions are

* $L << L_m$
* $L << L_\phi$

L => length of the conductor.

L_m => Mean free path.

L_ϕ => Length, an electron can travel before an inellastic collision [phase-coherence length]

* The electron doesn't hit anything as it travel through the material [No momentum or phase relaxation]

* Application:

* One particle application of ballistic transport.
  - Ultra-short-channel semiconducting FETS.

    (or)
  - Carbon Nanotube transistors

SPINTRONIC DEVICES:

* Spintronics

It is a field of a nanotechnology that deals with spin dependent properties of electrons and its implications in device applications.

* Spin transport electronics.

* Requirements for spintronics
  * Effective spin injection.
  * Slow spin relaxation
  * Exact spin detection.

* Spintronic Devices:

Spintronic devices are a combination of standard

Downloaded from EnggTree.com

EnggTree.com

microelectronic devices with spin dependent magnetic properties.

* In these devices, spin-orbit coupling plays a major role in determining the lifetime of the spin-polarization.

Principle:

* Information is stored (written) as spin-orientation (up or down)

* The spins attached to the mobile electrons carry the information.

* The information is retrieved (read) at a terminal.

* Types of spintronic Devices:

- Spin Field Effect transistor [spin-FET]
- Spin Valve
- Spin LED
- Quantum dots (or) spin-based computers.
- Hard Disk Drive (HDD) Read Head.
- Magnetic sensors.

* Advantages of spintronics

- High energy efficiency.
- Less heat generation.

* Applications:

- Memory storage.
- Quantum Computing
- Energy harvesting using spin-diodes.

⇨ Spin Field Effect Transistor (spin-FET)

A semiconductor channel contacted with two ferromagnetic electrodes constitute a spin field effect Transistor (spin-FET).

* Principle:

When electric field is applied, the electrons are injected and are polarized by ferromagnetic and drain into the semiconductor channel.

Downloaded from EnggTree.com

EnggTree.com

* Construction:

* Ferromagnetic source and drain contacts are located on two sides of a semiconductor channel.

* A gate voltage is used for transmitting & controlling the spin polarized electrons from source to drain.

Ferromagnet source, V_G, Ferromagnet drain, S, Gate, D, Semiconducting channel, Substrate (GaAs)

Ferromagnet source, V_G, Ferromagnet drain, S, D, S. channel, Substrate (GaAs)

Working:

* Case I:

when $V_g = 0$

→ injected electrons are anti-parallel, the net spin polarization decreases.

→ FET is said to be in OFF state.

* Case II: when $V_g > 0$

→ gate voltage $V_g >> 0$, the spin polarized electrons is controlled with electric field, spin reaches the drain.

* FET is said to be in ON state

* Advantages:

* Consume very less power.

* more sensitive.

* Applications:

* To create more sensitive automotive sensors.

* Store more data in limited storage space.

Quantum Well Laser:

A diode made of one dimensional square well, where active region is so narrow by quantum confinement is called quantum well laser.

* Types of Quantum Well lasers.

* Single Quantum Well (SQW) laser - Well laser with one active region

* Multi Quantum Well (MQW) laser = Well laser with many active region.

* Principle:

* In a quantum well laser, the semiconductor with smaller band gap has quantized energy level with high density of states,

Downloaded from EnggTree.com

EnggTree.com

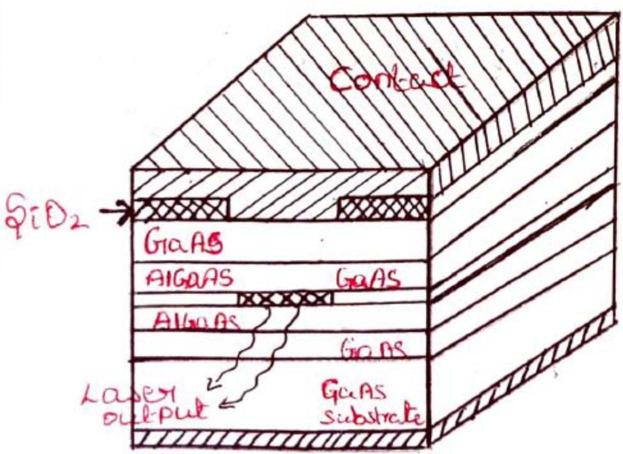
where the recombination takes place and produce laser output.

* Wavelength of light depends on width of the active region.

* Construction:

* Lower-band gap material GaAs is sandwitched between higher band gap material GaAlAs.

* Doped with p-type & n-type where two materials provided with metal contact for passing current.

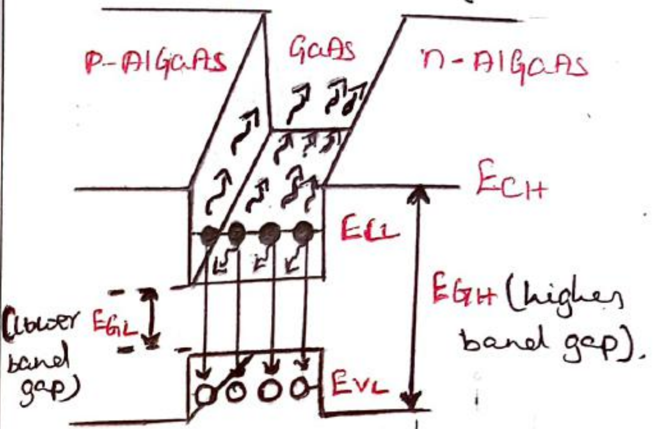


* P-type & n-type form well for the laser diode.

* Working:

* n-AlGaAs → Electrons } to GaAs layer
P-AlGaAs ⇒ holes }

* In active layer (well region) recombination of electrons & holes generate photons of frequencies.



* waves travel back & forth inside a cavity formed by two partially reflecting surfaces of the well.

* The waves enhanced by coherent stimulated emission by recombination electrons & holes.

* Advantages
* High modulation
* More light energy

* Disadvantages
* Exhibits small signal modulation
* Output power depends on input pumping.

* Applications
* Laser printing
* Material processing
* Fiber optic communication.

Downloaded from EnggTree.com