First Year Engineering (2019 Pattern)

Engineering Physics

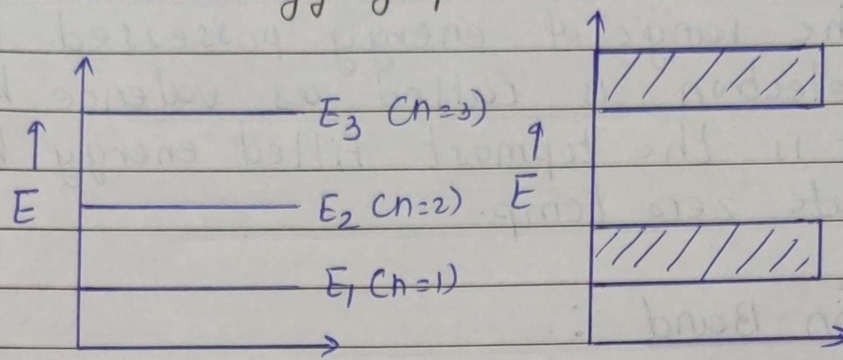
Unit 04 : Solid state Physics

(Notes from Exam Point of view)

Semiconductor (Solid State) Physics

Q. 1) Explain formation of bands in solid. Explain the terms valence band, conduction band, forbidden energy gap. [6 m]

⇒



- In case of isolated atom, energy of electron in any orbit is represented by single energy level

- However solid is formed by no. of atoms packed very close to each other. Every atom interacts with its neighbouring atom and hence slight change occurs in their energies.

- Therefore in solid, electron's energy in any orbit is represented by range of energy rather than single energy. level.

- Range of energy possessed by electron in an atom is called as energy band.

- If, N = No. of atoms in a solid
Then there will be 'N' energy levels in each energy band spaced very close to each other.

- Splitting of energy levels is more for outermost electrons and less for innermost electrons.

① **Valence Band :**

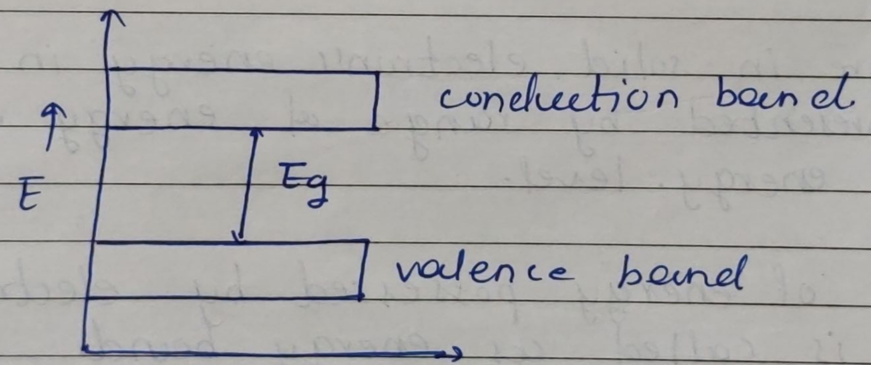
- The range of energy possessed by valence electron is called as valence band.
- It is the topmost filled energy band at absolute zero temp.

② **Conduction Band :**

- The range of energy possessed by conduction electrons (free electrons) is called as conduction band.

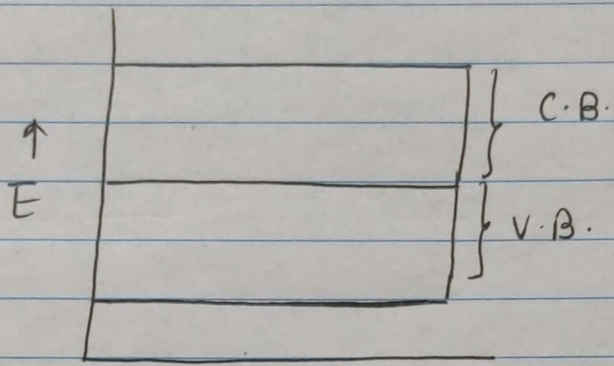
③ **Forbidden Energy Gap :**

- The energy gap present between conduction band and valence band is called as forbidden energy gap. (E_g)



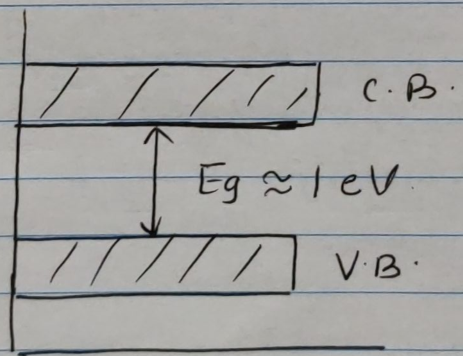
- Classification of Solids on the Basis of Energy bands :→

① <u>Conductors</u> :-



- In conductors, valence band and conduction band overlap on each other.
- Energy gap = 0
- ∴ Large no. of free electrons are available for conduction.

② <u>Semiconductors</u> :-

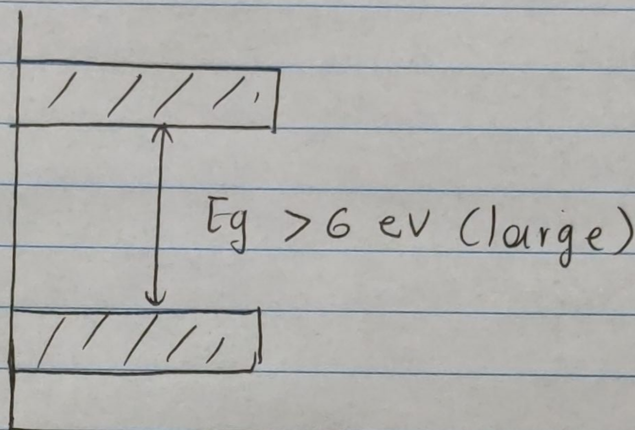


- In semiconductors energy gap between valence band and conduction band is very small.
- Their conductivity lies bet^n that of conductors and insulators.
- At 0 K, valence band is completely filled and C.B is completely empty. ∴ semiconductor at 0K,

acts as an insulator.

- As temp. increases, electrons in V.B., acquires enough energy to cross small energy gap and become free. Electrons move to C.B. Thus semiconductors and leave behind holes in V.B.
- Hence current is the sum of current due to electrons and holes.

③ **Insulators :-**



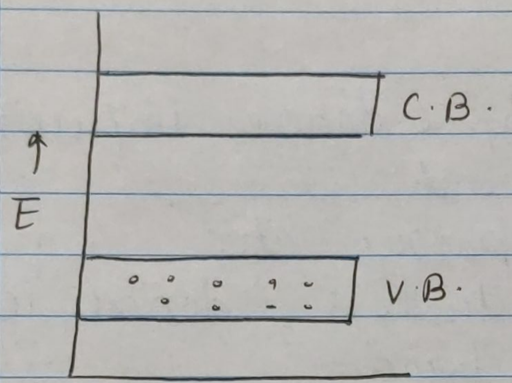
- In Insulators, energy gap is very large.
- ∴ Thermal energy can not excite electrons from V.B. to C.B.
- ∴ Valence band is completely filled and C.B. remains completely empty.
- ∴ These solids exhibits low electrical conductivity at all temp. & act as insulators.

- ## Classification of semiconductors :-

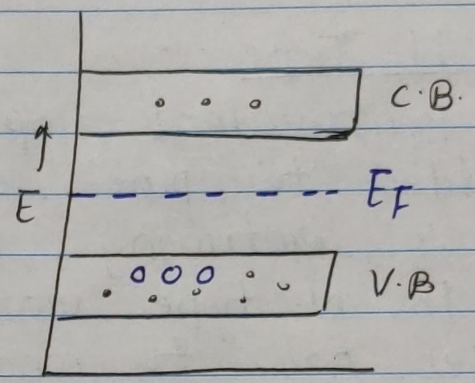
① **Intrinsic or Pure Semiconductors :-**

e.g. Si, Ge.

- No foreign atoms are added in semiconductors
- At 0K, Intrinsic semiconductors act as insulators because no free $\bar{e}$ are there in C.B.



(At 0K)



(At T > 0K)

- As temp. increases, some of the electrons from V.B. acquire energy and go to C.B. leaving behind holes in ~~ba~~ V.B.
- Hence current causes due to both the charge carriers, electrons as well as holes
- Here, $n_e = n_h = n_i$

where n_i = intrinsic charge carrier density.

- In intrinsic or pure semiconductors, fermi level lies at the centre of C.B. & V.B.

$$\therefore \boxed{E_F = \frac{E_c + E_v}{2}}$$

② Extrinsic Semiconductor :-

- To increase conductivity of pure semiconductors, controlled amount of foreign atoms are added to it, Then semicond. is called as extrinsic semicond.

- There are two types of extrinsic semicon.

① N-Type :

- Pentavalent impurity (donar impurity) is added to pure semicond.
- e.g. antimony, phosphrous etc.

∴ In N-type semiconductors, donar level lies near to condn band.

- Electrons are mejority charge carriers.

~~② P-Type~~

$$n_e >>> n_h.$$

② P-Type :-

- Trivalent impurity is added to pure semicond.
- e.g. boron, aluminium
- In P-Type semicond., acceptor level lies near to V.B.
- Holes are mejority charge carriers.

$$n_h >>> n_e$$

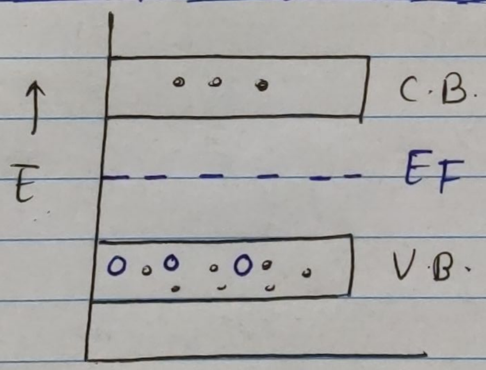
• Position of Fermi level in Semiconductor :-

Ques: Define Fermi level in semiconductors.
Show position of fermi level in intrinsic semiconductor
Show position of fermi level in P- Type and N- Type at low & high temp.

⇒ • Fermi level in Semiconductor :-

Fermi level in semiconductors is defined as, energy corresponding to centre of gravity of energy of electrons in C.B. & energy of holes in V.B.

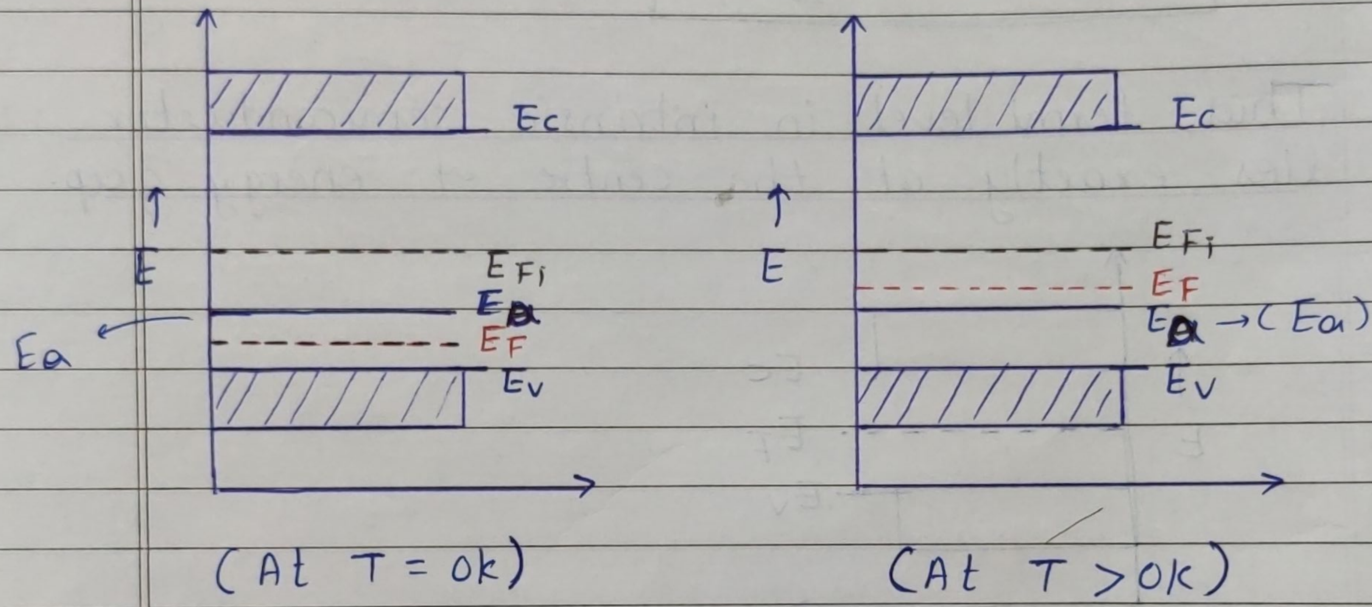
• Fermi level in Intrinsic Semiconductors :-



Fermi level lies at the centre of C.B. & V.B.

$$\therefore \boxed{E_F = \frac{E_v + E_c}{2}}$$

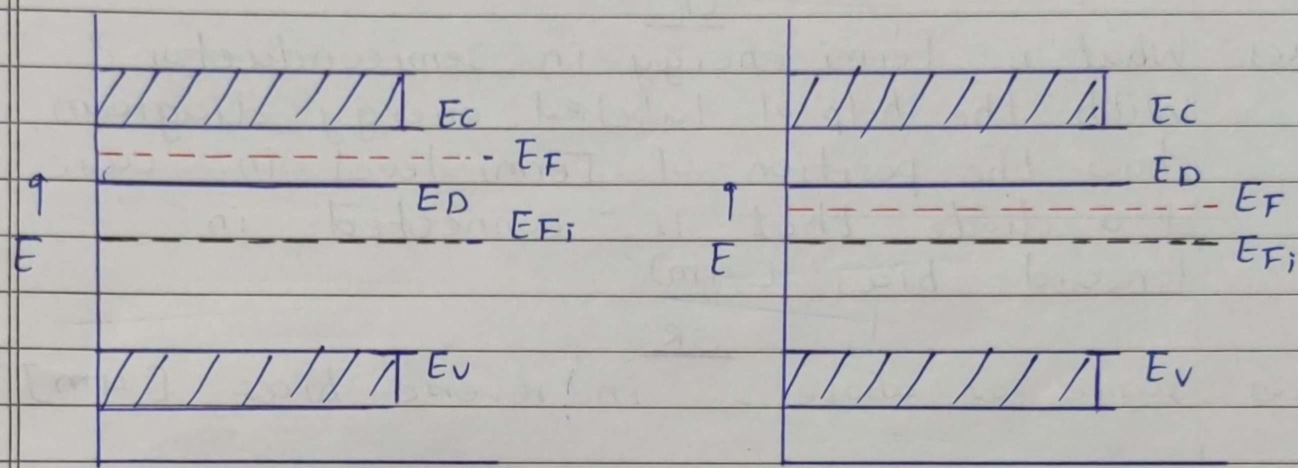
- Position of Fermi Level in P- type semicond.



- In P- type semiconductor, acceptor level lies just above valence band
- At T = 0k, acceptor atoms accept electrons from valence band and become positive ions leaving behind holes in V. B.
- ∴ Fermi level lies between acceptor level and valence band.

- At $T > 0K$, electrons from valence band get excited to conduction band
- ∴ Fermi level shifts above E_a but it lies well below E_{F_i}

• Position of Fermi Level in N-Type semiconductor :-



(At $T = 0k$)

(At $T > 0k$)

- In N-type semiconductor, donar level lies just below conduction band
- At $T = 0k$, donar atoms provide electrons to the C.B.
- Hence fermi level lies between conduction band and donar level.

- At $T > 0K$, some of electrons in V.B. also shift to the conduction band leaving behind holes in V.B.
- Hence Fermi level shifts down and lies just ~~above~~ below donar level (E_D) but well ~~below~~ above E_{F_i}

* Fermi Level

Ques: What is fermi level ? Explain Fermi-Dirac distribution function specifying meaning of each symbol.

⇒ **Fermi level :**

It is highest occupied energy level at absolute zero temperature

Fermi-Dirac Distribution Function :

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

where,

$P(E)$ = Probability of occupancy of energy level (E) at temp. T.

E = Energy level occupied at temp. T

E_f = fermi energy

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

1) when $P(E) = 1$ then it means that there is 100% probability that energy level E will be filled at temp T

2) when $P(E) = 0$ then it means that there is 100% probability that energy level E will not be filled at temp T

3) when $0 < P(E) < 1$, say 0.5 then it means that there are 50% chances that energy level will be filled at temp T

Ques. Write the formula for Fermi - Dirac distribution function. Find probability of occupancy of energy level at $T = 0k$ for $E < E_F$ and $E > E_F$ and at $T > 0k$ for $E = E_F$

OR

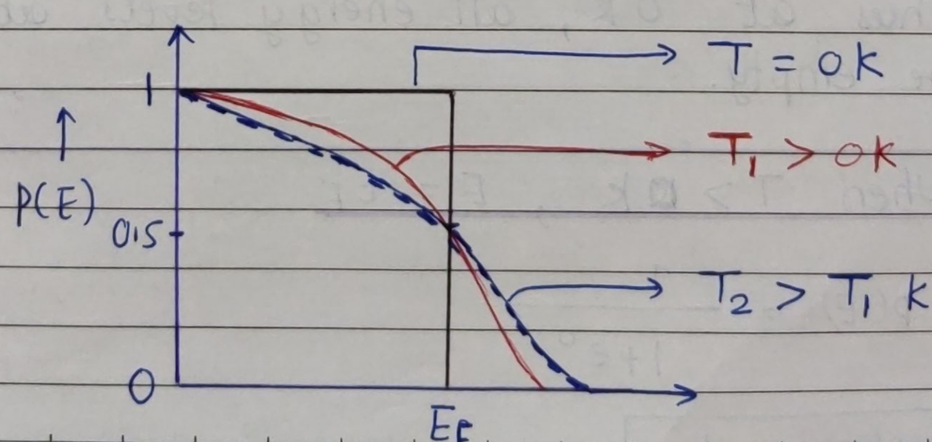
Write the formula for Fermi - Dirac distribution fun. Draw in the same figure the Fermi - Dirac probability versus electron energy at $T = 0k$, $T_1 k$ and $T_2 k$ ($T_2 > T_1 > 0k$). Explain the significance of the figure.

⇒ • Fermi Level :
It is highest occupied energy level at absolute zero temperature.

• Fermi - Dirac Distribution Function :

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

• P(E) Vs electron energy diagram :-



Significance of fig :

① when $T = 0k$, $E < E_F$

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

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

$$\boxed{P(E) = 1}$$

Thus at 0k, all energy levels below E_F are occupied by electrons.

② when $T = 0k$, $E > E_F$

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

$$\boxed{P(E) = 0}$$

Thus at 0k, all energy levels above E_F are empty.

③ when $T > 0k$, $E = E_F$

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

$$\boxed{P(E) = \frac{1}{2}}$$

Thus at $T > 0k$, probability of occupancy of Fermi level is 0.5

And probability of occupancy of energy level below E_F is less than one (decreases) and that of above E_F increases i.e. greater than zero

★ Position of Fermi level in Intrinsic semiconductor

Ques Using Fermi - Dirac distribution function, derive an expression for the position of Fermi energy level in intrinsic semiconductor.

OR

Ques. Using Fermi- Dirac Distribution function, prove that the position of Fermi level in the intrinsic semiconductor is at the centre of forbidden energy gap. [6m]

⟹ Consider a semiconductor,

Let,

E_c = Energy of conduction band

E_v = Energy of valence band.

N_c = No. of electrons in conduction band at T K

N_v = No. of electrons in valence band at T K.

N = Total no. of electrons in V.B. & C.B. at T K

$$\boxed{N = N_c + N_v} \quad \text{--- (1)}$$

- Now if,

$f(E_c)$ = Probability of occupancy of electrons in conduction band

$$f(E_c) = \frac{N_c}{N}$$

$$\therefore N_c = N \cdot f(E_c)$$

$$\boxed{N_c = \frac{N}{1+e^{(E_c-E_F)/kT}}}$$

- Similarly,

$$\boxed{N_v = \frac{N}{1+e^{(E_v-E_F)/kT}}}$$

- Now,

$$N = N_c + N_v$$

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

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

By solving this,

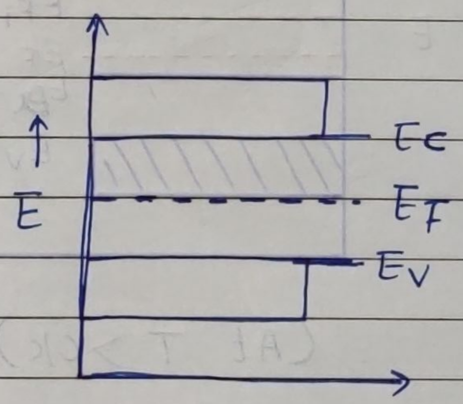
$$e^{\frac{E_C + E_V - 2E_F}{kT}} = 1$$

$$\therefore \frac{E_C + E_V - 2E_F}{kT} = 0$$

$$\therefore E_C + E_V - 2E_F = 0$$

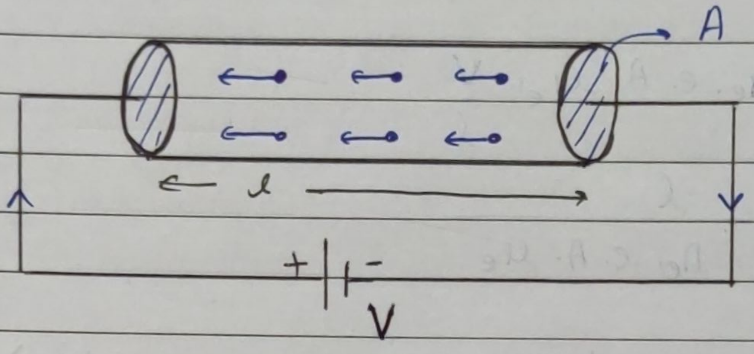
$$\therefore \boxed{E_F = \frac{E_C + E_V}{2}}$$

Thus, fermi level in intrinsic semiconductor lies exactly at the centre of energy gap.



* Conductivity of conductors and semi conductors :

Ques: Derive expression for conductivity of conductors. [6m]



- Consider a conductor,
  - l = length of conductor
  - A = Area of cross section.
  - V = Voltage applied across conductor
  - E = Electric field generated.
  - v_e = drift velocity of electron
  - μ_e = mobility of electron
  - e = charge of electron.
  - n_e = electron density.

- n_e = electron density = No. of $\bar{e}$ per unit volume

$\therefore$ No. of $\bar{e}$ in a conductor $(N) = n_e \cdot A \cdot l$

Total charge $(Q) = N \cdot e = n_e \cdot e \cdot A \cdot l$

Total current flowing thr. conductor,

$$I = \frac{Q}{t} = \frac{n_e \cdot e \cdot A \cdot l}{t}$$

$$\therefore \boxed{I = n_e \cdot e \cdot A \cdot v_e} \quad --- \quad v_e = \text{velocity} = \frac{l}{t}$$

$$\therefore I = n_e \cdot e \cdot A \cdot \mu_e E \quad --- \quad (v_e = \mu_e E)$$

$$\therefore I = n_e \cdot e \cdot A \cdot \mu_e \cdot \frac{V}{l}$$

$$\therefore \frac{V}{I} = \frac{l}{n_e \cdot e \cdot A \cdot \mu_e}$$

$$\therefore \frac{RA}{l} = \frac{1}{n_e \cdot e \cdot \mu_e} \quad ---- \quad (R = \frac{V}{I})$$

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

Now,

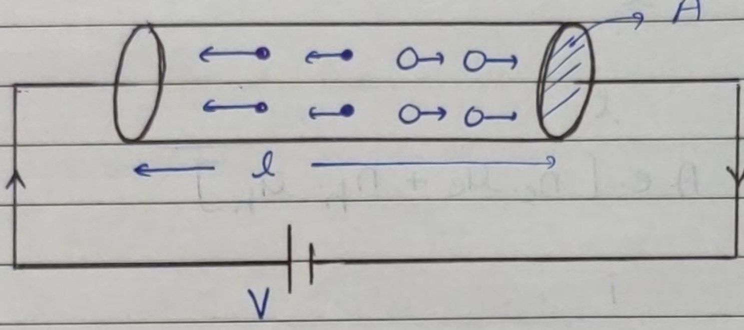
conductivity $(\sigma) = \frac{1}{\rho}$

$$\therefore \boxed{\sigma = n_e \cdot e \cdot \mu_e}$$

This is expression for conductivity of conductor.

Ques. Derive expression for conductivity of semiconductor [6 m]

⟹



- Consider a semiconductor in which current flows due to both the charge carriers.

- l = length of semiconductor , A = area of cross sectio
  V = voltage applied across semiconductor
  E = Electric field developed.
  n_e = electron density n_h = hole ~~mobility~~ densi
  μ_e = electron mobility μ_h = hole mobility
  v_e = drift velocity of $\bar{e}$ v_h = drift velocity of holes.

- Now, in semiconductor,

$$I = I_e + I_h$$

$$I = n_e \cdot e \cdot A \cdot v_e + n_h \cdot e \cdot A \cdot v_h$$

$$= A \cdot e \left[n_e \cdot v_e + n_h \cdot v_h \right]$$

$$= A \cdot e \left[n_e \cdot \mu_e \cdot E + n_h \cdot \mu_h \cdot E \right] \quad \text{---} \quad (v = \mu E)$$

$$I = A \cdot e \cdot E \left[n_e \cdot \mu_e + n_h \cdot \mu_h \right]$$

$$I = A \cdot e \cdot \frac{V}{l} \left[n_e \cdot \mu_e + n_h \cdot \mu_h \right]$$

$$\frac{V}{I} = \frac{l}{A \cdot e \cdot [n_e \cdot \mu_e + n_h \cdot \mu_h]}$$

$$\frac{RA}{l} = \frac{1}{e[n_e \cdot \mu_e + n_h \cdot \mu_h]}$$

$$\therefore \rho = \frac{1}{(n_e \cdot e \cdot \mu_e + n_h \cdot e \cdot \mu_h)}$$

$\therefore$ conductivity $(\sigma) = \frac{1}{\rho}$

$$\therefore \boxed{\sigma = n_e \cdot e \cdot \mu_e + n_h \cdot e \cdot \mu_h}$$

① **Intrinsic Semiconductor** :

$n_e = n_h = n_i$ = intrinsic charge carrier density

$$\boxed{\therefore \sigma_i = n_i \cdot e \cdot [\mu_e + \mu_h]}$$

② **N-Type semiconductor**,

$$n_e >> n_h$$

$$\therefore \boxed{\sigma_{N\text{-Type}} = n_e \cdot e \cdot \mu_e}$$

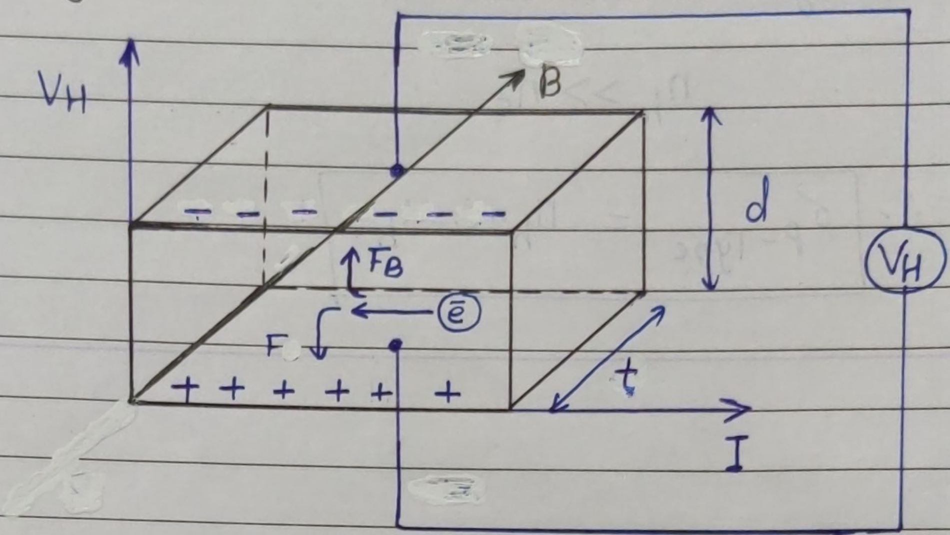
③ P- Type semiconductor :

$$n_h >> n_e$$

$$\therefore \boxed{\sigma_{P\text{-Type}} = n_h \cdot e \cdot \mu_h}$$

★ Hall Effect :

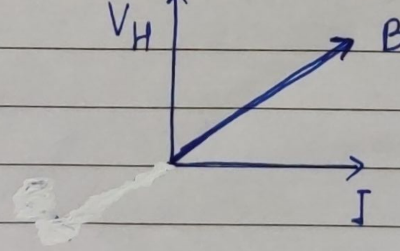
Ques Explain hall effect. Derive equation for Hall voltage and Hall coefficient [6m]



Hall effect :

When current carrying conductor or semiconductor is kept in transverse magnetic field, voltage is developed in a direction perpendicular to direction of current as well as direction of magnetic field

This voltage is called as Hall voltage and the effect is called as Hall effect



From diagram,

Let,

I = current flows along the x-axis

B = magnetic field applied along z-axis

V_H = Hall voltage produced along y-axis.

E_H = Electric field developed along y-axis.

d = width of material , t = Thickness

- Magnetic force on charge carriers,

$$F_B = B.e.v \quad \text{-----} \quad (1)$$

- Electric force on charge carriers,

$$F_E = e.E_H \quad \text{-----} \quad (2)$$

- Under equilibrium,

$$F_E = F_B$$

$$\therefore \quad e.E_H = B.e.v$$

$$\therefore \quad E_H = B.v$$

$$\therefore \quad \frac{V_H}{d} = B.v \quad \text{----} \quad \left(E_H = \frac{V_H}{d}\right)$$

$$\therefore \quad \boxed{V_H = B.v.d} \quad \text{-----} \quad (3)$$

Now we know,

$$I = n \cdot e \cdot A \cdot v$$

$$\therefore \boxed{v = \frac{I}{n \cdot e \cdot A}}$$

- $\therefore$ Eqn. (3) becomes,

$$V_H = B \cdot v \cdot d$$

$$V_H = \frac{B \cdot I \cdot d}{n \cdot e \cdot A}$$

$$V_H = \frac{1}{n \cdot e} \frac{B \cdot I \cdot d}{A}$$

$$V_H = \frac{1}{n \cdot e} \cdot \frac{B \cdot I \cdot d}{d \times t} \quad \text{-----} \quad (A = d \times t)$$

$$\boxed{V_H = \frac{1}{n \cdot e} \frac{B \cdot I}{t}} \quad \text{-----} \quad \text{Hall voltage}$$

- Now,

$$\frac{1}{n \cdot e} = \text{constant} = R_H = \text{Hall coefficient}$$

$$\therefore \boxed{R_H = \frac{1}{n \cdot e}} \quad \text{-----} \quad \text{Hall coefficient}$$

Applications of Hall effect :

1. To determine types of semiconductor.
2. To determine charge carrier concentration.
3. $\sigma = n \cdot e \cdot \mu$

$$\therefore \mu = \frac{\sigma}{n \cdot e}$$

$$\therefore \boxed{\mu = R_H \cdot \sigma}$$

To determine mobility of charge carrier.

★ P-N Junction Diode

Ques: With the help of neat labelled diagram, explain the working of the diode in forward and reverse bias in comparison with unbiased diagram. [6 m]

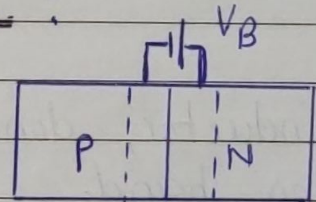
OR

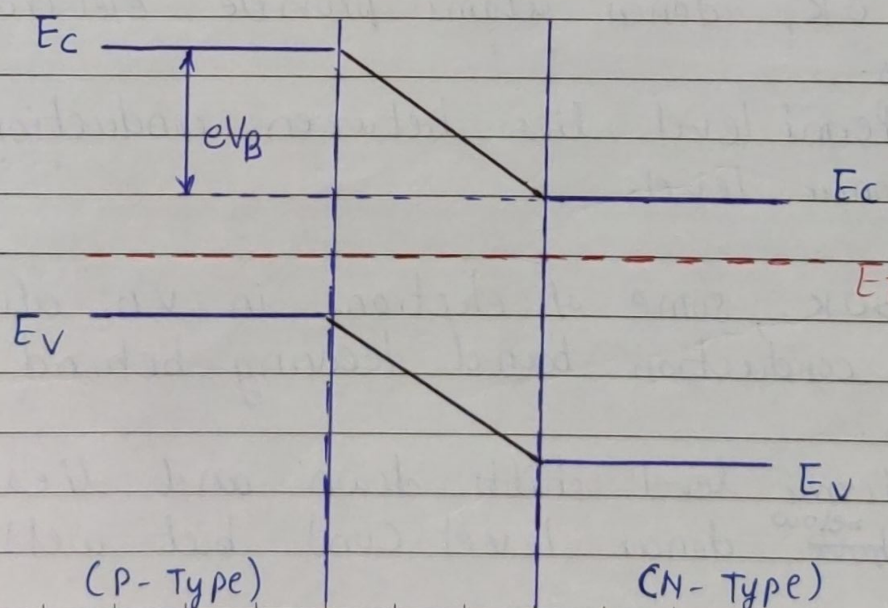
Ques: What is Fermi energy in semiconductor? With the help of labeled energy diagram, show the position of Fermi level in case of a diode that is connected in Forward bias. [4m]

OR

Ques: Same as above --- in reverse bias. [4m]

⇒ ① Unbiased :





- In P. type semiconductor, fermi level lies closer to valence band and in N- type semiconductor fermi level lies closer to conduction band.

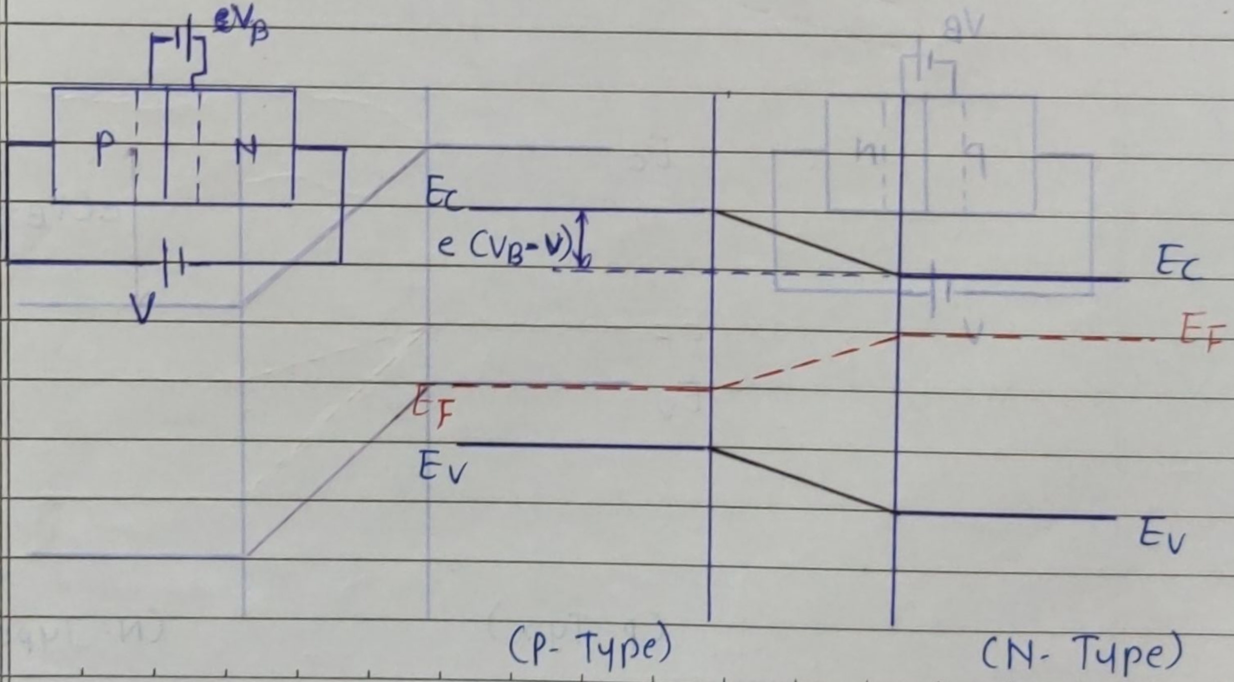
- When PN junction is formed, diffusion of charge carriers take place across the junction till fermi levels equilize.

- To equilize fermi levels, bands on either side shift accordingly

- ∴ Energy hill (eV_B) is formed between P & N region

- ∴ Further diffusion of charge carriers stop and current does not flow thr. the diode.

② Forward Bias :-



- In forward bias P-region is connected to +ve terminal of battery and n-region is connected to -ve terminal of battery.

- It increases energy of electrons in N-region.

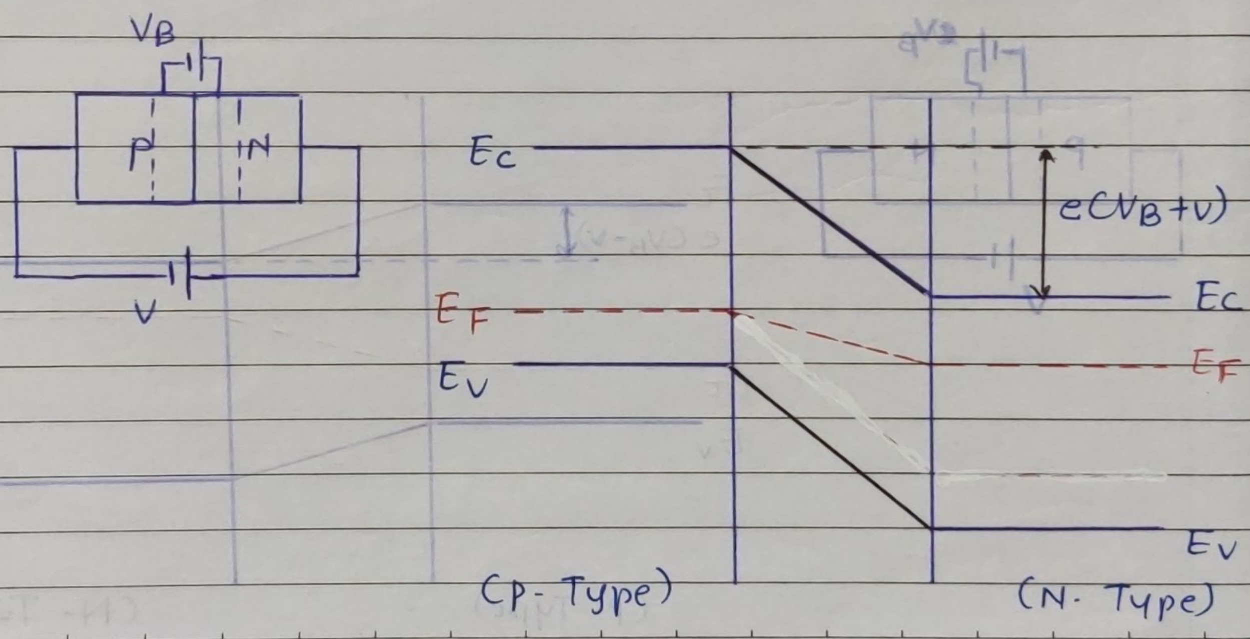
- ∴ Fermi level on N-side is raised by energy eV.

- Bands on either side shift accordingly

- The energy hill height reduces to $e(V_B - V)$

- ∴ charge carriers can diffuse thr. junction and current flows thr. the diode.

③ Reverse Bias :-



- In reverse bias, P-region is connected to -ve terminal while N-region is connected to +ve terminal of battery.

- It decreases energy of electrons on N-side.

- ∴ Fermi level on N-side is lowered by eV.

- Bands shifts accordingly.

- ∴ Energy hill height increases to $e(V_B + V)$

- ∴ Charge carriers can not diffuse across the junction and so current get reduced in reverse bias.

- Very small current flows, due to minority charge carriers.

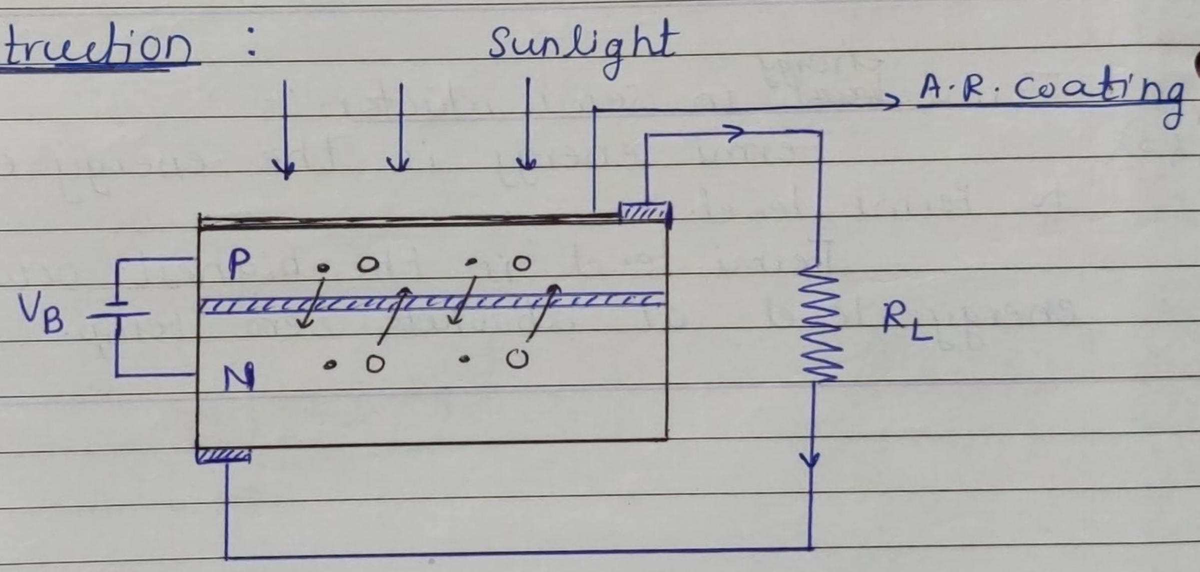
★ Solar Cell

Ques: What is photovoltaic effect & Explain construction and working of solar cell.
Draw IV characteristics of solar cell and define Fill Factor.

- **Photovoltaic effect :-**
  Conversion of light energy into electrical energy when certain semiconductors are exposed to light is called as photovoltaic effect.

- **Solar Cell :**
  A device which converts light energy into electrical energy is called as solar cell.

- **Construction :**



- It consists of silicon PN junction diode with its P-layer is made very thin, so that incident light reaches to PN junction.

- Metal contacts are provided on top and bottom surfaces which act as electrodes.

- Antireflection coating is given over top surface to avoid reflection of incident light

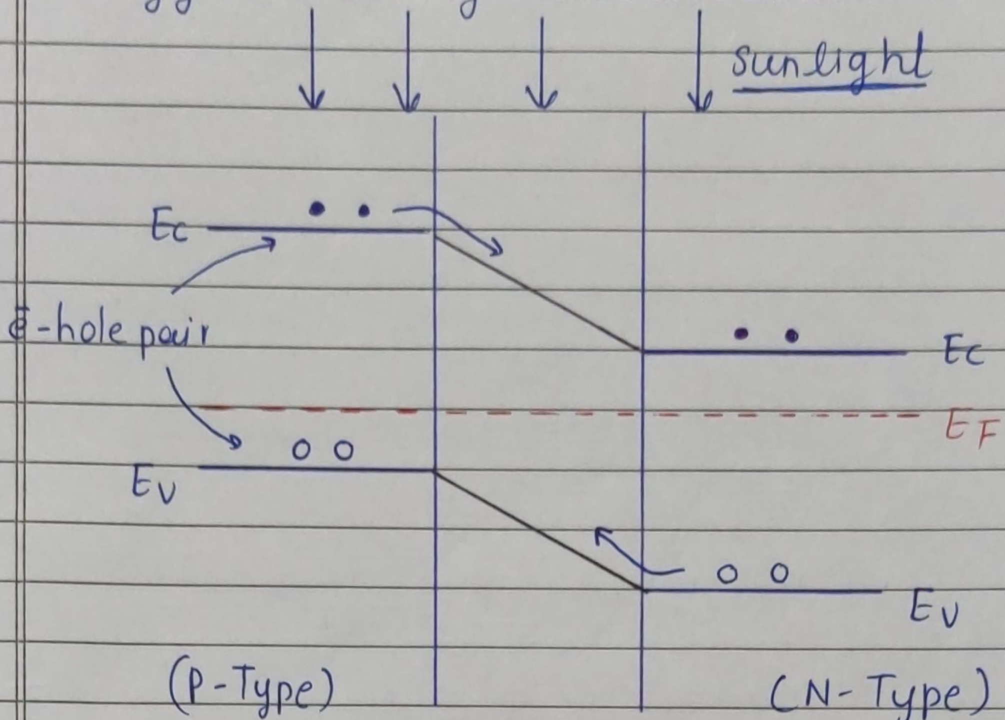
• **Working :**
- when light falls on solar cell, it reaches to PN-junction.
- Light consists of photons of energy $h\nu$.
- These photons are absorbed by silicon atoms in P region as well as n-region.
- Thus electron-hole pairs are generated in both the regions.
- when they come to PN-junction, they face built in potential (potential barrier.)

- Electrons from P-region move towards N-region and holes from N-region move towards P-region.

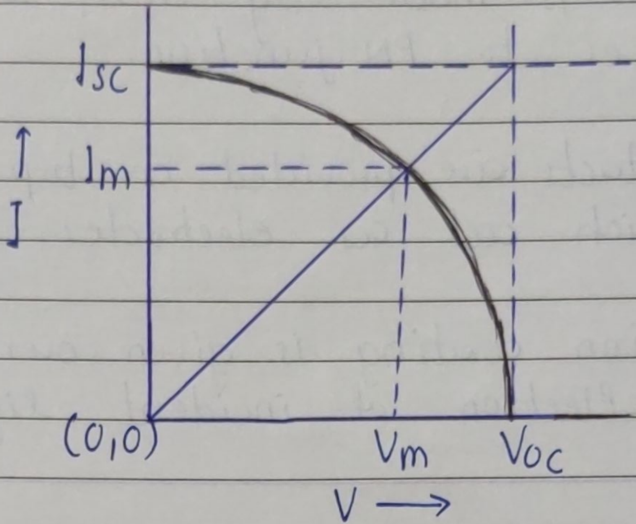
- Thus accumulation of electrons and holes take place on both sides of junction which gives rise to voltage, called as photoemf

- when load is connected across the solar cell, current flows thr. it.
- Thus light energy is converted into electrical energy.

- **Energy Level Diagram of solar cell :-**



- IV characteristics of solar cell :-



Theoritical power output of solar cell $= I_{sc} \cdot V_{oc}$

$$\therefore \boxed{P_{ideal} = I_{sc} \cdot V_{oc}}$$

Actual maximum power output of solar cell $= I_m \cdot V_m$

$$\therefore \boxed{P_{max} = I_m \cdot V_m}$$

- Fill - Factor :

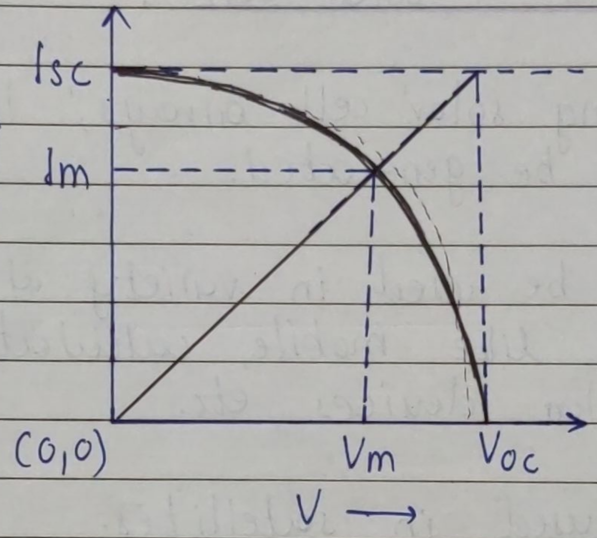
It is defined as ratio of actual maximum power to ideal power.

$$\therefore \boxed{F.F. = \frac{I_m \cdot V_m}{I_{sc} \cdot V_{oc}}}$$

Ques: Explain working of solar cell.
Give significance of cell parameters, I_{sc}, V_{oc} and fill factor. State applications of solar cell.

⟹ **Working of solar cell :**

Parameters of solar cell :



① **Open circuit voltage (V_{oc}) :**
when load resistance $R_L = \infty$,
Output voltage from solar cell is called as open circuit voltage. $V = V_{oc}$

② **Short circuit current (I_{sc}) :**
when load resistance $R_L = 0$,
output current measured is called as, short circuit current.
$I = I_{sc}$

③ **I_m and V_m :**
These are maximum current and maximum voltage obtained from solar cell.

④ **Fill factor (F.F.) :**

It is the ratio of maximum power to ideal power of solar cell.

$$\therefore \quad F.F. = \frac{I_m \cdot V_m}{I_{sc} \cdot V_{oc}}$$

- **Applications of solar cell :**

① By using solar cell arrays, large scale power can be generated.

② It can be used in variety of electrical equipments like mobile, calculator, street light, solar devices etc.

③ It is used in satellites.

④ It is used in remote areas where other sources of energy are not possible.

Ques: State measures to improve efficiency of soler cell.

⇒ Ways to improve efficiency of solar cell :-

① Fill Factor [Proper Utilization of Surface area]:-

- Full utilization of surface area is required for highest efficiency of solar cell.

- It depends on shape of solar cell.

- eg. round or moon shaped solar cell has less fill factor than square shape.

② Solar cell Glazing :

- For longer life, solar cells must be protected from external factors like rain, hail, snow etc.

- So thin films are coated on surface of solar cell which are having highest transmittivity

- A.R. coatings are coated on solar cell to reduce reflection of light

③ Solar Panel Orientation :

- Orientation of solar panel can be done in such a way that maximum sunlight can fall on solar cell for maximum time.

4. Solar Trackers :

- Solar trackers rotate solar panels so that they always face the sun.

- They are the great way to enhance output power.

5. Light concentrators :

- Light concentrators such as Fresnel lens or mirrors are used to concentrate sunlight on solar cell surface so that maximum light pass thr. it and increases output power.

Formulae

I Formulae Based on Conductivity :-

$$\boxed{\sigma = n e \mu} \qquad \boxed{\sigma = \frac{1}{\rho}}$$

1) $\sigma_{conductor} = n_e \cdot e \cdot \mu_e$

2) $\sigma_{pure\ semicon.} = n_i e (\mu_e + \mu_h)$

3) $\sigma_{N-Type} = n_e \cdot e \cdot \mu_e = n_d \cdot e \cdot \mu_e$

4) $\sigma_{P-Type} = n_h \cdot e \cdot \mu_h = n_a \cdot e \cdot \mu_h$

n_e = electron concentration
n_h = hole concentration
μ_e = electron mobility , μ_h = hole mobility
n_a = acceptor atom concen.
n_d = donar atom concent.

5) If carrier concentration (n_e or n_h) is not given,

1) No. of parent atoms $= \dfrac{\text{Density} \times \text{Avagadro's no.}}{\text{Atomic weight}}$

2) Charge carrier concen. (n_e) $= \dfrac{\text{No. of parent atoms}}{\text{part of dopant atoms}}$

(II) Drift velocity, Field Gradient, Energy gap:

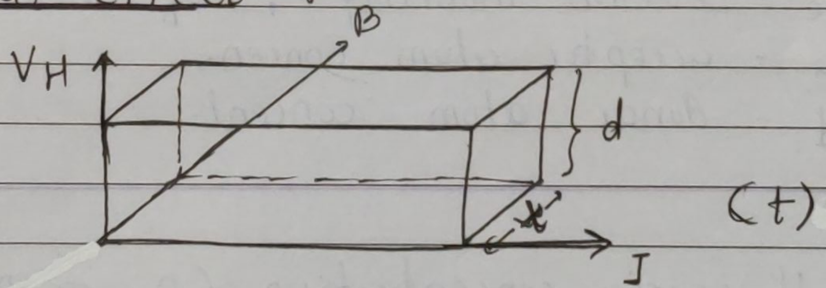
(1) $V \propto E$ $\therefore$ $\boxed{V = \mu E}$ (v = drift velocity)

(2) $E = \frac{V}{l}$ --- (V = voltage)

(3) $E_g = h\nu = \frac{hc}{\lambda}$

v = drift velocity
E = Electric field gradient
c = velocity of light
E_g = energy gap.

(III) Hall effect:



(1) $V_H = \frac{B \cdot I \cdot d}{n \cdot e \cdot A}$

V_H = Hall voltage
d = width of material
A = Area of cross section
n = charge carrier concen.

(2) $V_H = R_H \cdot \frac{B \cdot I \cdot d}{A}$ R_H = Hall coefficient

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

(3) $V_H = R_H \cdot \frac{B \cdot I \cdot d}{t \times d} = R_H \cdot \frac{B \cdot I}{t}$

t = thickness of material.

(4) $J = \frac{I}{A}$ --- J = current density.

(5) $\sigma = n \cdot e \cdot \mu$

$\therefore \mu = \frac{\sigma}{n \cdot e}$

$\therefore \boxed{\mu = R_H \cdot \sigma}$

IV Fermi Level :

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

(2) $\frac{(E_C - E_F) \text{ at } T_1}{T_1} = \frac{(E_C - E_F)_{T_2}}{T_2}$

$P(E)$ = Probability of occupancy of energy level E
E_F = Fermi level
k = Boltzman con. $= 1.38 \times 10^{-23}$ J/K