UNIT-V - SOLID STATE PHYSICS

Free Electron Theory :- (classical approach)

Drude & Lorentz has proposed free electron theory on the basis of following assumption:

- In conductors (Metals), the free electrons or valence electrons are free to move inside a conductor just like a gas molecule.
- since, electrons behave like gas molecule, therefore the kinetic theory of gas will be applicable on electrons.
- In the absence of E.F, the electrons move randomly, whereas the collisons will be elastic (No loss of energy).
- When the E.F is applied, the free electrons will start accelerating opposite to the applied field. This is known as Drift current.
- There is no electrostatic force of attraction b/w +ions & electrons.

Electrical conductivity & Drift current

→ The electrical conductivity denoted by (σ) is the measure of the ability of a material to conduct & electric current from it. It's units are S/m.

→ consider an electron, which is in motion in conductor under the influence of applied electric field. If e is the charge, m is the mass of electron, E is the E.F, Then the force on electron is given as

$$F = eE \quad — (1).$$

Also, $$F = ma \quad — (2)$$

a = acceleration

from (1) & (2)

$$eE = ma$$

$$a = \frac{eE}{m}$$

Rate of change of velocity w.r.t time is acceleration,

$$\therefore \frac{dv}{dt} = \frac{eE}{m}$$

$$dv = \frac{eE}{m}\,dt.$$

on integrating both side

$$\int dv = \frac{eE}{m}\int dt$$

$$v = \frac{eEt}{m} + c. \quad \text{—— (3)}$$

When, $t = 0$, $v = 0$.

From Equation (3)

$$C = 0. \quad \text{—— (4)}.$$

From Equation (3) & (4)

$$v = \frac{eEt}{m}$$

When the transfers time is the collision time that is Relaxation time (τ)

Therefore. $v = \dfrac{eE\tau}{m}$

When the velocity of electron is drift velocity this drift velocity is the velocity of electrons, when e^- starts moving opposite to the applied field. The V_d is the avg. velocity.

So, the drift velocity is given as

$$v_d = \frac{eE\tau}{2m} \quad \text{--- (5)}$$

A.C.T Ohm's law, the current density

** $$\boxed{J = \sigma E} \quad \text{--- (6)}$$

Since, the current density is the current

$$\boxed{J = \frac{I}{A}} \quad \text{--- (7)}$$

From Equation (6) & (7)

$$\frac{I}{A} = \sigma E$$

$$\sigma = \frac{I}{AE} \quad \text{--- (8)}$$

The drift current is given as

$$\boxed{I = e v_d n A} \quad \text{--- (9)}$$

Where n = is no. of free electrons.

On substituting value of (9) in (8)

$$\sigma = \frac{e v_d n \cancel{A}}{E \cancel{A}}$$

$$\boxed{\sigma = \frac{v_d e n}{E}} \quad \text{--- (10)}$$

On substituting the value of v_d from Equation (10) to Eq. (5)

$$\sigma = \frac{ne^2 \tau}{2m}. \quad \text{— (11)}$$

Now, the mean free path (λ) – [The avg. dist. travelled by the electrons b/w successive collisions is known as mean free path]

$$\lambda = \tau v.$$

$$\tau = \frac{\lambda}{v}. \quad \text{— (12)}$$

On substituting the value of τ from (12) to (11).

$$\sigma = \frac{ne^2 \lambda}{2m}. \quad \text{— (13)}$$

The above expression represent electrical conductivity of free electrons.

Temperature dependency of electric conductivity.

→ Lorentz has applied the K.T.G for free electrons to explain the temp dependency of sigma.

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$$\frac{1}{2}mv^2 = \frac{3}{2}KT$$

$$mv^2 = 3KT$$

$$mv = \frac{3KT}{v} \quad \text{—} \quad (14)$$

From Eq. (13) (ε) (14)

$$\sigma = \frac{ne^2\lambda v}{6KT},$$

The above expression shows that the electric conductivity, with inc. in temperature σ will decrease.

$$\frac{1}{2}mv^2 = \frac{3}{2}KT$$

$$mv^2 = 3KT \qquad mv = \frac{3KT}{v}.$$

$$\boxed{\sigma = \frac{ne^2\lambda v}{6KT}}$$

Hall Effect :-

When any current carrying conductor is placed in transverse magnetic field, a potential is developed in a conductor in direction perpendicular to both current & magnetic field. This phenomena is known as Hall effect.

Derivation of Hall Effect:

Force on charge carriers due to produced Hall electric field (E_H)

$$F = q\,\vec{E_H} \quad \text{--- (1)}$$

Force on charge carriers due to produced/applied magnetic field is given as.

$$F_m = q\,(\vec{V_d} \times \vec{B}) \quad \text{--- (2)}$$

where V_d is the drift velocity.

At Equilibrium stage both the forces must be Equal.

$$F_e = F_m$$

From Equation (1) & (2)

$$\cancel{q} E_H = \cancel{q}\,(\vec{V_d} \times \vec{B})$$

$$E_H = \vec{V_d} \times \vec{B} \quad \text{--- (3)}$$

The magnitude of Equation (3) is

$$E_H = V_d B \sin\theta$$

When $\theta = 90°$,

$$E_H = V_d B \quad \text{— (4)}$$

current density J is current per unit area

$$J = \frac{I}{A} \quad \text{— (5)}$$

The drift current is given as

$$I = V_d e n A \quad \text{— (6)}$$

On substituting Eq. (6) in Eq. 5

$$J = \frac{V_d e n \cancel{A}}{\cancel{A}}$$

$$J = n e V_d$$

$$V_d = \frac{J}{ne} \quad \text{— (7)}$$

substituting the value of V_d from (7) to Equation (4).

$$E_H = \frac{J}{ne} B \quad \text{— (8)}$$

If b is the width of the conductor then Hall electric field can be releated to potential as

$$E_H = \frac{V_H}{b}.$$

where V_H is the Hall's voltage & it can be written as

$$V_H = b E_H \quad \text{— (9)}.$$

on substituting the value of E_H from Eq. (8) to Eq. (9).

$$V_H = b \frac{J B}{ne}$$

where $\frac{1}{ne}$ is the coefficient of Hall's effect & it is represent by $R_H = \frac{1}{ne}$.

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

In case of electron the Hall's coefficient will be −ve & is written as

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

From ohm's law, the current density is ∝ to electric field

$J = \sigma E_x$

The resistivity $\rho = \frac{1}{\sigma}$

$\sigma = \frac{1}{\rho}$

Therefore, $J = \frac{E_x}{\rho}$ — (10).

On substituting the value of J from Eq. (10) to Eq. (8).

$$E_H = \frac{\frac{E_x}{\rho} \cdot B}{ne}$$

$$E_H = \frac{E_x \cdot B \cdot ne}{\rho}$$

$$\rho E_H = E_x B ne$$

$$\frac{E_H}{E_x} = \frac{Bne}{\rho}$$

$$\frac{E_H}{E_x} = \frac{B}{\rho ne}$$

The above expression gives the Relation b/w E_H & E_x.

With the help of above relation, we can measure conductivity & Resistivity of the solids.

Wiedemann - Franz Law.

→ This Law gives the ratio of Thermal conductivity & Electrical conductivity

$$\boxed{\frac{K}{\sigma} = \frac{3}{2}\left(\frac{K_B}{e}\right)^2 T}$$

K → Thermal conductivity

σ → Electrical conductivity.

K_B → Boltzmann's constant.

T → Temperature.

e → charge.

Diffusion current :-

→ The diffusion current is the current in which charge moves from higher concn to lower conn. under the effect of Electric field.

→ The diffusion current is caused due to unequal distribution inside solids, b/w electrons & holes.

Fermi - Dirac - Distribution.

- Fermi energy & fermi levels

→ The energy of the highest occupied level at 0°c absolute energy is known as Fermi-energy & the energy level is represented as Fermi level.

$$f(E) = \begin{cases} 1 & E < E_f \\ 0 & E > E_f \end{cases}$$

- The Fermi-Dirac function is given as:

$$\boxed{f(E) = \frac{1}{e^{(E-E_f)/KT} + 1}}$$

$\because$ E_f = Fermi Energy,
k = Boltzmann's constant.

Case 1 :- At absolute Temperature T = 0

$\frac{E-E_f}{KT}$, where T=0.

$$\frac{E-E_f}{KT} = \begin{cases} +\infty & E > E_f \\ -\infty & E < E_f. \end{cases}$$

$$f(E) = \frac{1}{e^{-\infty}+1} = \frac{1}{0+1} = 1 \quad , \quad [e^{-\infty} = 0]$$

$$f(E) = \frac{1}{e^{\infty}+1} = \frac{1}{\infty+1} = 0.$$

Case 2 :- At some temperature T, E = E_f

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

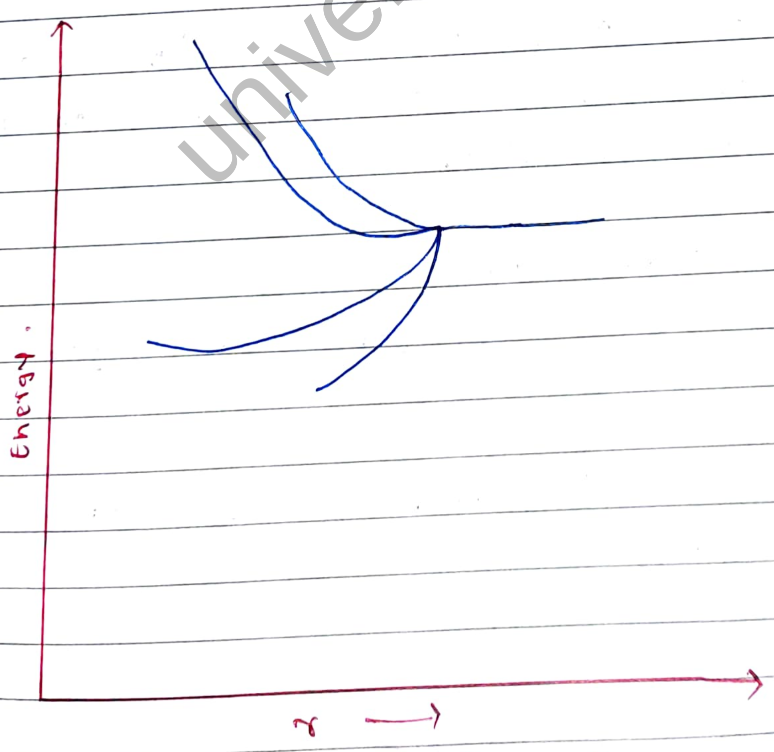
$$f(E) = \frac{1}{2} \quad (e^0 = 1)$$

So, the Fermi level is the energy level at which the half probability of finding electron is $\frac{1}{2}$.

Band Theory of solids, Formation of Allowed Forbidden Energy bands.

Electrons are asumed to be tightly bound to the individual atoms, when atoms are bring together to form solids by interaction between the neighbouring atoms causes the electrons energy level of individual atoms to be split, this is how the bands are forming.

The band theory follows Pauli's exclusion principle.



(Interatomic distance) .

As, the r decreases the energy level get into energy band

Allowed Energy band.

→ Allowed energy bands are range of energy le within a material where electrons are allowed exist. It is further categoeries into two that is valence band & conduction band.

- Valence band.

→ Range of energy level where electrons are most likely to be found it is highest occ energy level that is fully occupied at 0 absolute temp.

- Conduction band

→ It is the Range of energy level above valence band where e^- are free to move within the material.

Forbidden Energy bands

→ Also known as Energy gap & band gap where e^- are not allowed to exist.

Insulators, semiconductors & conductors in terms of Band Gap.

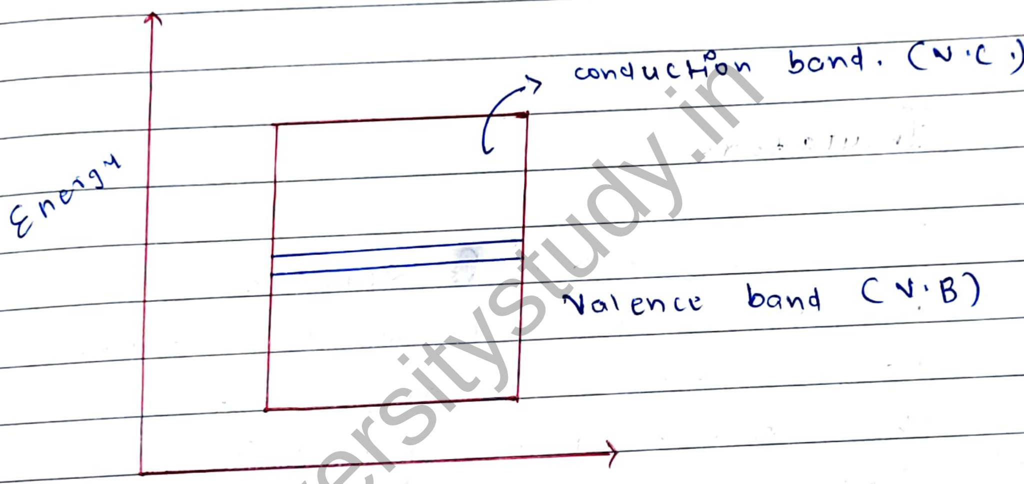
- conductors.

→ In such materials there is no forbidden gap b/w V.B & C.B

→ The e^- from valence band to conduction band can freely enter due to overlapping of bands.

→ Because of overlapping very low potential diff. can cause continous flow of current.

→ The band gap for conductor is $E_g = 0\,eV$



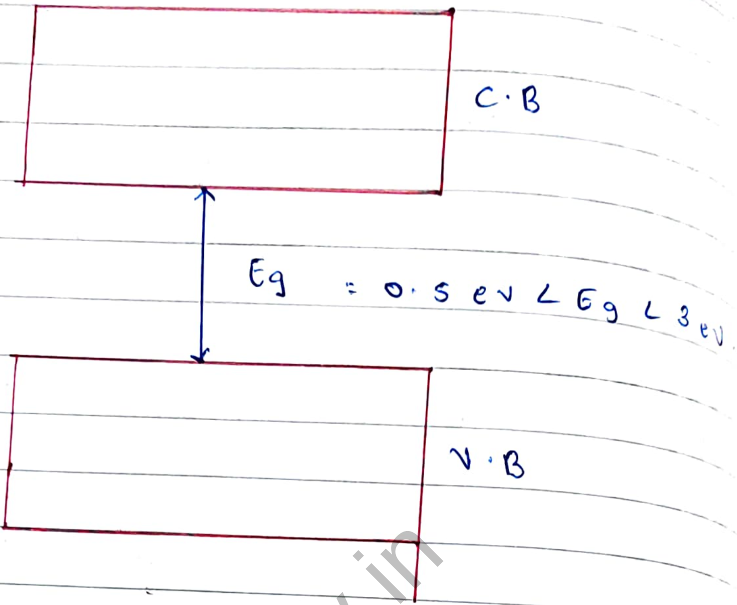
Semiconductors

→ In case of s.c. the forbidden gap is very small.

→ At 0K temp, the conduction band is Empty & the valence band is completely filled.

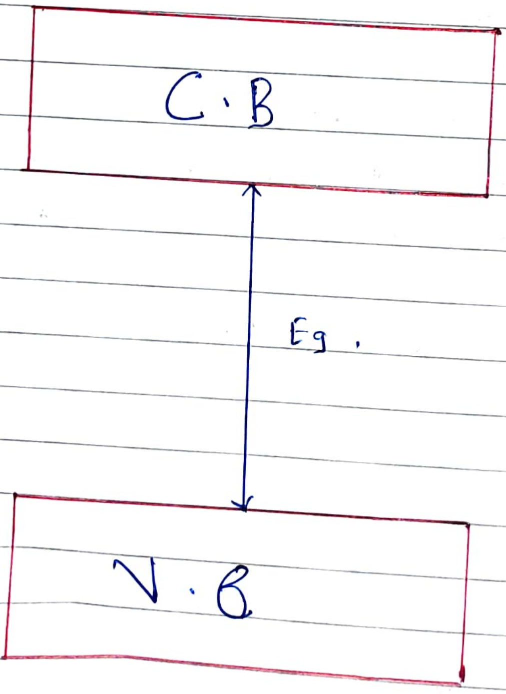
→ When a small amount of energy is supplied the electrons can easily jump from V.B to C.B.

→ The energy gap in case of s.c is $0.5\,eV < E_g < 3\,eV$.



Insulators

- The forbidden gap is very Large.
- No electrons are available for conduction.
- Large amount of energy is needed to move the electrons from V.B to C.B.
- The Energy gap is > 3 ev



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Semiconductors & it's Types.

Semiconductors are the materials which have conductivity in between conductors & insulators

$$10^{-8}\ s/cm < \sigma < 10^{3}\ s/cm.$$

Insulators   Conductors.

Types of semiconductor

The semi-conductors are categories as follow

Semiconductors

- Intrinsic
- Extrensic.
  - P-Type (acceptor ions)
  - N-Type (donor ions)

Intrinsic semiconductors.

→ such types of materials are pure semiconductors for e.g. si & Ge that are not doped with external impurity.

Extrinsic S.C.

→ In such type of materials some specific impurities are doped to modify their electrical properties.

p-Type

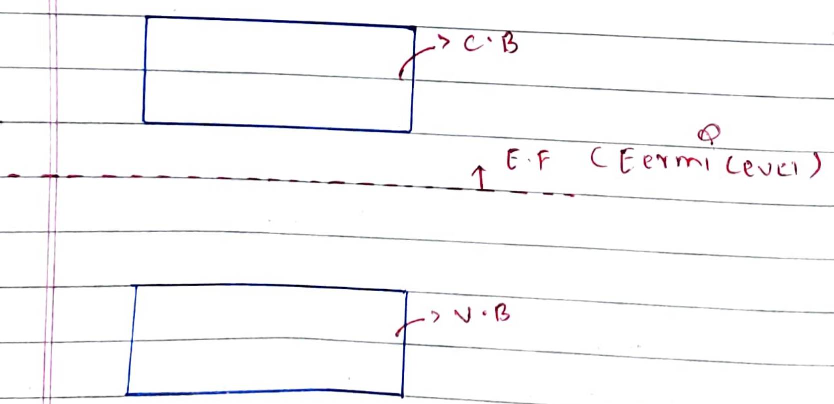
→ In such materials trivalent elements are doped, the doping will introduce excess holes, and the overall conductivity will decrease. For e.g. Group 13 elements.

N-Type

→ In such type of S.C the pentavalent impurity is doped. The doping will introduce excess e^-, which will enhance the electrical conductivity.

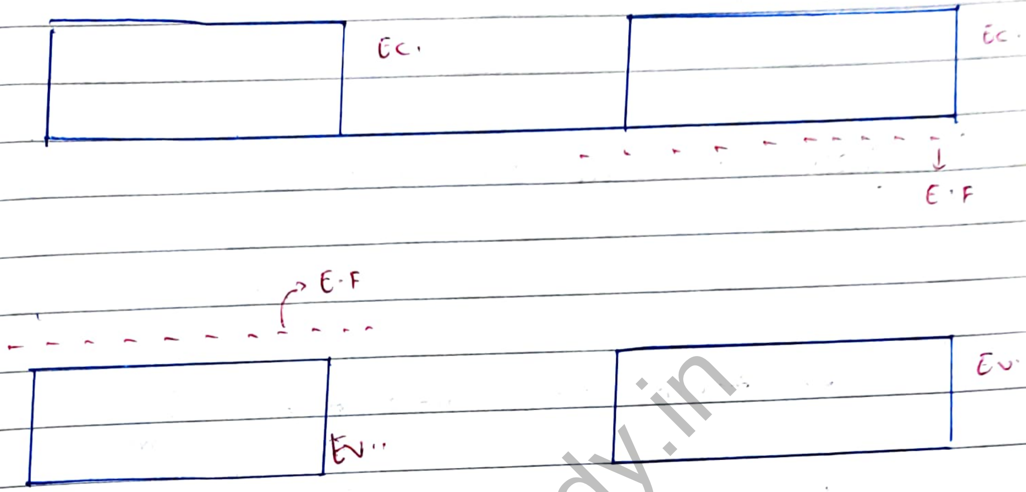
Intrinsic & Extrinsic S.C on the basis of Fermi Level.

Intrinsic.



Extrinsic.

P-Type N-Type.



→ The fermi level in terms of I.S.C will lies b/w V.B & C.B

→ In P-type the fermi level lies to near to the V.B

→ N-Type " " " "
" C.B.

Effective Mass (M^*)

The concept of effective mass is given to acount the diff. between free electrons & the electrons in crystal lattice. (M^*) is different from the free electron mass. It is depend on the nature of crystal lattice & varies with the direction of motion of e^-.

The effective mass does not change the original mass of the particles rather it represent how the particles behave in a solid material as comparison to free space.

Derivation of Effective mass.

The K.E of e^- is $\frac{1}{2} m v^2$

In terms of momentum $E = \frac{p^2}{2m}$ — (1) [∵ p = mv]

Since $p = \hbar k$ — (2).

substituting Eq. (2) in (1).

$$E = \frac{\hbar^2 k^2}{2m} \quad \text{— (3).}$$

on diff. Eq. (3) w.r.t k

$$\frac{dE}{dk} = \frac{\cancel{2}\hbar^2 k}{\cancel{2}m}$$

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m} \quad \text{— (4)}$$

on diff Eq. (4) w.r.t k

$$\frac{d^2E}{dk^2} = \frac{\hbar^2}{m} \quad \text{— (5).}$$

In case of crystal lattice, the mass m will be Equal to effective mass m^*

$\because \quad m = m^*$

∴ Eq. 5 can be written as

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

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

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

The above expression represent the effective mass

where $\frac{d^2E}{dk^2}$ is curvature of band

From Eq. (3) $E = \frac{\hbar^2 k^2}{2m}$

Put $E = y$

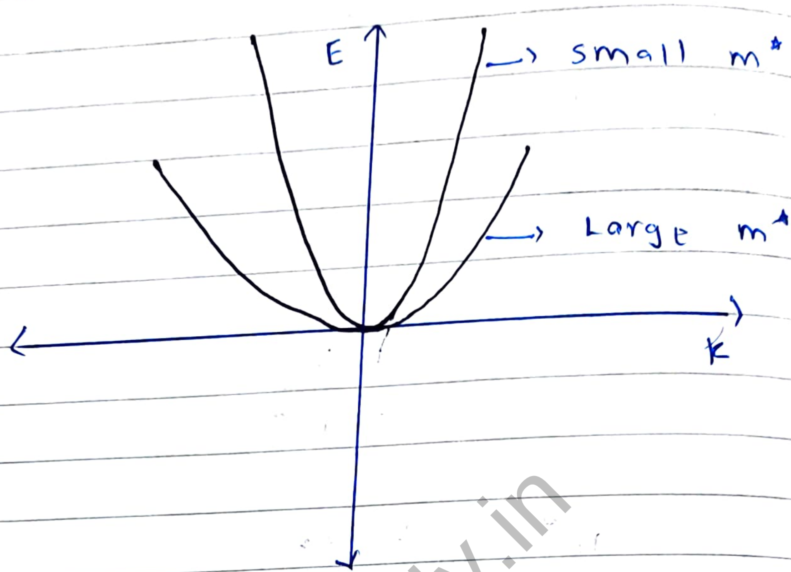
$K = x$

&. $\frac{\hbar^2}{2m} = c$.

$$\boxed{y = cx^2}$$

The above Expression represent parabola

So the E-k diagram can be plotted as



Points

→ m^* is positive near the bottom of all b
→ m^* will be -ve near the top of all b

Direct & Indirect band gap : semi-condu

Direct band-gap semiconductors

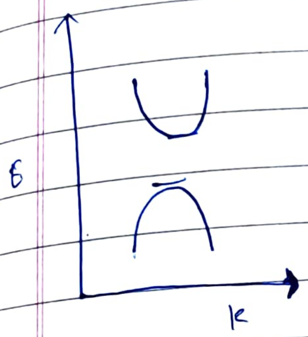
E-K diagram when the lowest energy po of the conduction band lies directly above heighest Energy point of the valence band a semiconductors, the move of e^- across the band gap is direct.

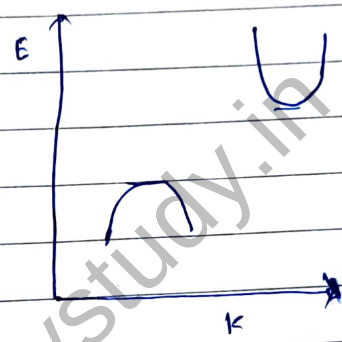
For ex. GaAs & Cds

Indirect band gap : semi-conductors.

when the heighest energy point of the V.B is not directly lying below the lowest point of the conduction band, the transfer of e^- is indirect

For. ex:- Si & Ge





(wave no.
or wave
vector)

Solar Cell

→ The solar cells are also known as photovoltic cells, that can convert sunlight directly to the electricity through the process known as photovoltic effect.

solar cells based on photo-voltic effect where semi-conductors are made up of silicon. The material of solar cell will absorb the photon & generate a flow of electric current as a result of absorption.

The solar cells is consists of P-N type semiconductors.