# UNIT-4

## Band Theory of Solids:-

**Band theory of Solids:-** This is the theory of valence electron which are Nearly free.

Free electron theory was Successful in Explaining the various Electronic & thermal properties of Metal like-

I) Specific Heat

II) Temperature Susceptability

III) Temperature dependence of Electrical Resistivity.

But it can't Explain the Distinction between Conductor Insulator & Semiconductor.

Band theory Explain that Each atom has a discrete set of Energy levels

1S, 2S, 2P, 3S, 3P --------.

The Splitted Energy levels are (becomes So Numerous) So Close together forming Energy bands.

Na - $1S^2 2S^2 2P^6 3S^1$

3S - 3S level is the First occupied level to be Splitted into band.

2P - 2P level doesn't Split until the interatomic distance becomes Smaller.

OR Energy bands in solid correspond to Energy level in Atom.

* Electrical Properties in solid depend upon its Energy band Structure.

Depending on the Nature of band occupation by electron and on the width of forbidden band, all the solids can be classified as conductors, insulator & semiconductor.

Valence band:- Filled level form a band known as valence band.

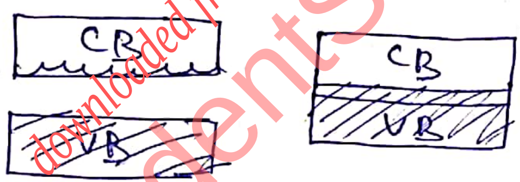
Conduction band:- Unfilled level form an another band known as conduction band.

Energy gap:- V.B & C.B seprated by some energy gap known as forbidden Energy gap.

## Classification of Solids:-

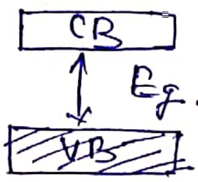
Solids can be classified into three types:-

1) Metal or Conductor:- C.B either partially filled or V.B & C.B partially overlap each other.






II) Insulator:- VB is completely filled and CB is completely empty & forbidden energy gap is quite large.




III) Semiconductor:- At 0K in semiconductor VB is completely & CB is completely empty. Energy gap is smaller than insulator.

## Semi conductors:-

A solid substance whose conductivity lies between an insulator and that of most metals. (Either due to addition of impurity or because of temperature effect).

## Types of Semi conductors:-

I) Intrinsic semiconductor II) Extrinsic Semiconductor

I) Intrinsic Semiconductor:- A pure semiconductor is known as intrinsic semiconductor.

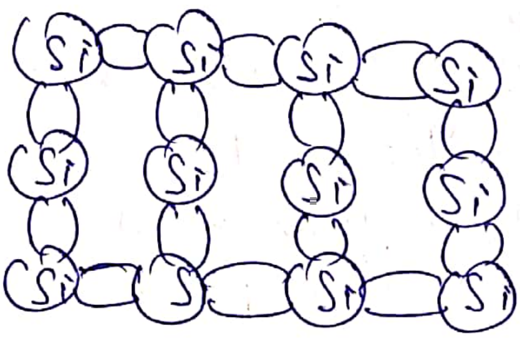
1) On the basis of Band theory:-

At 0K semiconductors are insulators but at room temp. Some electron gain energy due to thermal and moves from VB to CB.

* Vacancy is created in VB called Hole.
* Motion of hole in VB and electron in CB is Responsible for Electronic conduction.

II) On the basis of crystal structure:- Atoms are strongly bound by covalent bond.

→ On receiving Additional Energy some electron break their bond and produce free electron & equal No. of Holes.




Thus effective current in semiconductor is the sum of Electronic current & Holic current.

## Extrinsic Semiconductor:-

Process of Addition of impurity to a Pure Semiconductor. Doped Semiconductor called Extrinsic Semiconductor.

### Types of Extrinsic Semiconductor:-

I) N-type Semiconductor  II) P-type Semiconductor.

### I) N-type Semiconductor:-

Intrinsic Semiconductor doped with Pentavalent Impurity atom.

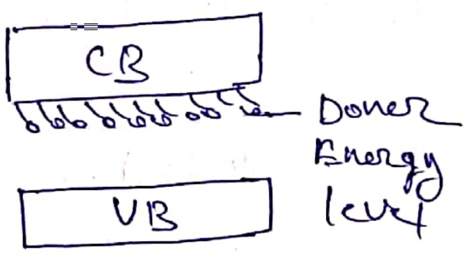
1) on the basis of crystal structure:-

* The impurity atom when Mixed with Si or Ge atom, form covalent bond with Neighbouring Si or Ge atom.
* At room temperature some covalent bond break and Produce equal Number of Holes and Free electrons.
* The Number of electrons are large compare to holes.
* Electrons are Majority charge carrier and Holes are Minority charge carriers.

→ Conduction is Mainly due to Electron + Holes.

2) on the basis of Band theory:-

→ When Impurity atom generate a New Energy level just below the CB known as doner energy level.




→ Now it is easy for them to jump from VB to CB.

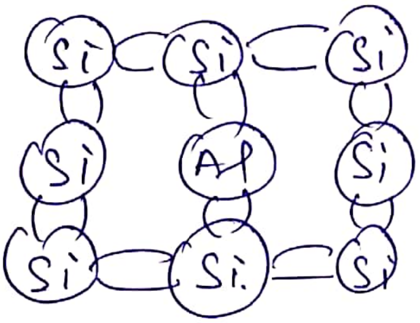
→ All electron of doner energy level jumps to CB at room temperature.

→ Some electron of VB also jumps to CB.

Hence the Number of electron in CB is large as Compare to VB.

# P-type Semiconductor:-

## on the basis of crystal structure:-




- When trivalent impurity atom is Mixed with Si or Ge, they replace Si or Ge atom and form Covalent bond with. Neighbouring Si or Ge.

→ Number of holes are very large as compare to Electrons. (due to trivalent impurity)

→ At room temperature covalent bond break and Produce equal Number of Holes and electrons.

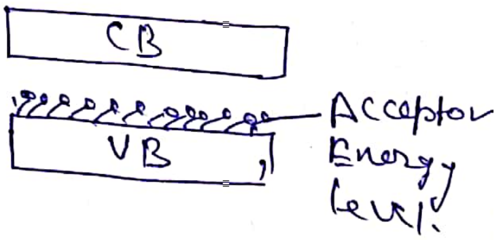
→ Holes are Majority and electron are Minority charge carrier.

⇒ conduction is Mainly due to Holes, therefore such Semi-conductor known as P-type Semiconductor.

## on the basis of band theory:-

Impurity atom generate an energy level just above the top of valence band, this Energy level known as acceptor level.

→ Thus electron from VB easily shift to acceptor level and generate holes in VB.




⇒ Electron from VB also goes to CB generating equal Number of Holes in VB.

→ Hence holes are Majority charge carrier electrons are Minority charge carrier in P-type Semi conductor.

# Difference between..

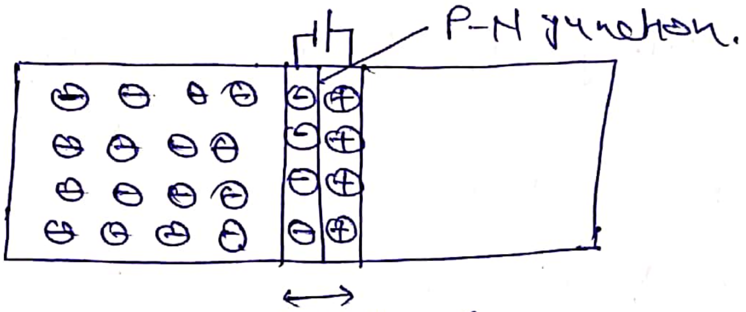
I)

| Intrinsic Semi conductor | Extrinsic Semi conductor. |
| --- | --- |
| I) Pure Semi conductor | 1) Impure Semi conductor |
| II) $n_h = n_e$ | 2) $n_h \neq n_e$ |
| III) Conductivity is low | III) conductivity is High. |
| IV) Conductivity depend only on temperature | IV) Conductivity depend on temperature and concentration of Doping.. |

| n-type Semi conductor | P- type Semi Conductor. |
| --- | --- |
| I) Impurity atom is Pentavalent | I) Impurity Atom is Trivalent |
| II) Electrons are Majority & Holes are Minority charge carriers. $n_e > n_h$ | II) Electrons are Minority and holes are Majority charge carriers $n_h > n_e$ |
| III) Impurity atom is known as Donor atom | III) Impurity atom is known as acceptor Atom. |
| IV) Donor level is formed just below the conduction band | IV) Acceptor level is formed just above the valence band |
| V) Conduction is Mainly due to electrons | V) Conduction is Mainly due to holes. |

**P-N junction diode:-** when P-type crystal is placed in contact with n-type crystal then common surface of contact of P & n type semiconductor is known as P-N junction diode.

**Depletion region & Potential barrier:-**




when a P-N junction is formed, holes move from p to n region and electrons move from n to P region through the junction (due to difference in concentration of charge carrier in two region).

* The holes and electrons diffusing towards each other combine near the junction. Thus a layer is formed near the junction (with junction in the middle), which doesn't have any type of free charge carrier and is called depletion region.
* Depletion Region prevent the further movement of electron & holes through the junction.
* Thus a barrier is setup in P-N junction against the movement of charge carrier.

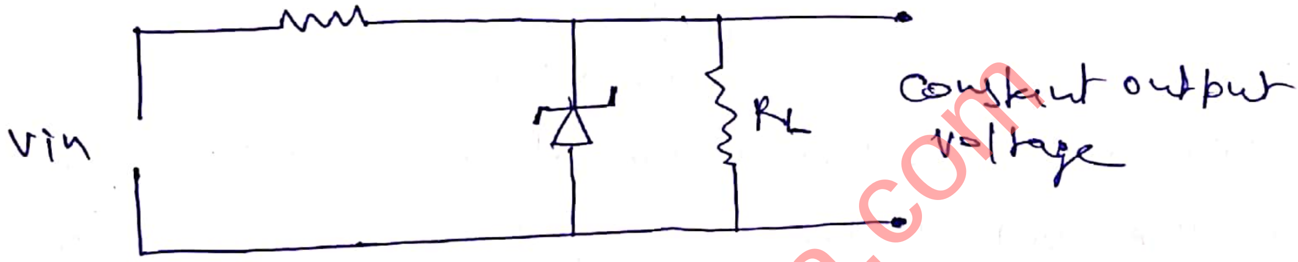
Note → I) For Ge it is 0.3V II) For Si it is 0.7 V.

III) Magnitude of potential barrier depend on nature of semiconductor & doping concentration.

~~(IV) ... depletion ... barrier for Si~~

**Zener Diode:-** This diode consist of special heavily doped P-n junction, designed to conduct in reverse direction when a certain specified voltage is reached.


**Zener diode as voltage Regulator:-** The circuit diagram using zener diode as voltage Regulator is shown in Fig.




→ Ex. When input voltage increase, resistance of zener diode decrease (due to breakdown of zener Diode) and hence current through zener diode increase.

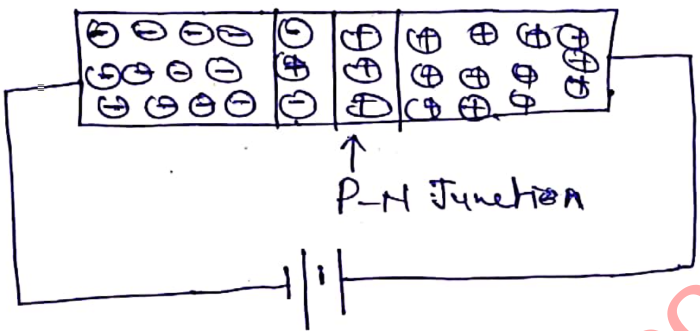
→ As a Result of this large voltage drop occurs across dropping resistance R. Hence output voltage across RL remains constant.

→ When input voltage decrease:- resistance of zener diode increase and hence current through zener diode decrease. So small voltage drop takes place across R. Hence output voltage RL maintained constant.

**Biasing:-** Applying an External Potential Difference on the faces of junction is called Biasing.

It is of two type -

1) **Forward Biasing:-** In this biasing Negative terminal of the battery is connected to 'N' region and Positive terminal is connected to p- region.




Characteristics:-

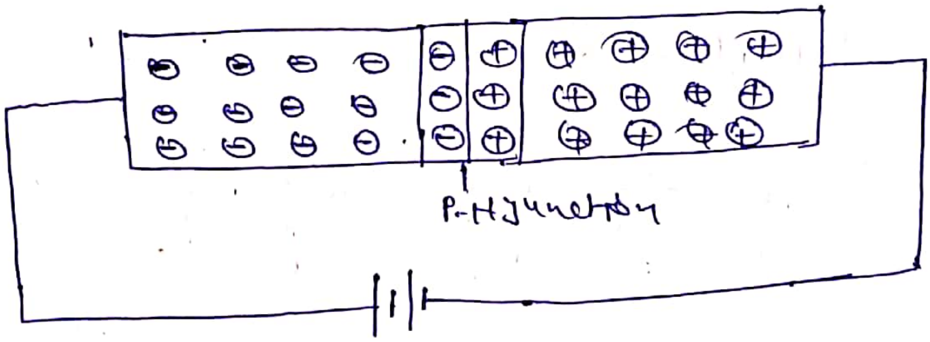
1) A current of mA order flows through the junction.

II) In Semiconductor current is due to both type of Majority charge Carrier.

III) In forward biasing diode offer low resistance and width of depletion region decrease.

IV) Resistance of P-N junction Diode is Non-ohmic

ii) **Reverse Biasing:-** In this biasing +ve terminal of the battery is connected to n-type semiconductor and -ve terminal is connected to p-type semiconductor.




**Characteristics:-** i) A small current of μA order flows through the junction due to the movement of charge carrier.

ii) In external circuit current is due to free electrons.

iii) In reverse biasing P-N junction offers high resistance and width of depletion region increase.

iv) In reverse biasing current increase suddenly at a particular reverse biased voltage known as breakdown voltage. This phenomenon is known as avlenche breakdown. At this voltage diode may damage.

# P-N Junction (Energy band diagram with Fermi Energy)

## I) P-N Junction (No bias).

When P-N Junction is in Equilibrium, number of carrier diffusing from P side to N-side is Equal to Number of carrier diffusing from N to P side. Consequently there is no current across junction.

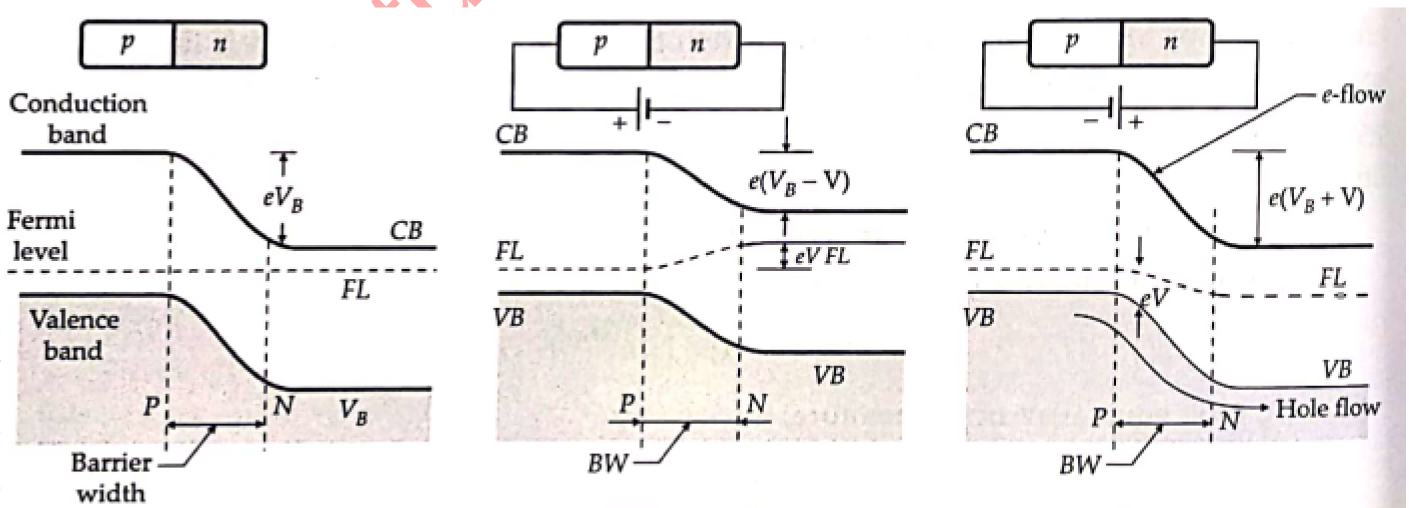
## II) P-N-Junction (Forward bias)

Fermi level rise by eV and their Energy band adjust their position so as to suit the elevation of Fermi level. Due to increase in Energy on N-side Potential barrier is reduced to $e(V_B - V)$.

## III) P-N-Junction: (Reverse Bias)

It lower the Fermi level on N-side by an amount of eV raising the barrier height $e(V_B + V)$ and increasing the depletion width too. Consequently current is very much Reduced in Reverse biasing of P-N Junction.






(a) No bias (b) Forward bias (c) Reverse bias

## Important
## Kronig Penny Model:-

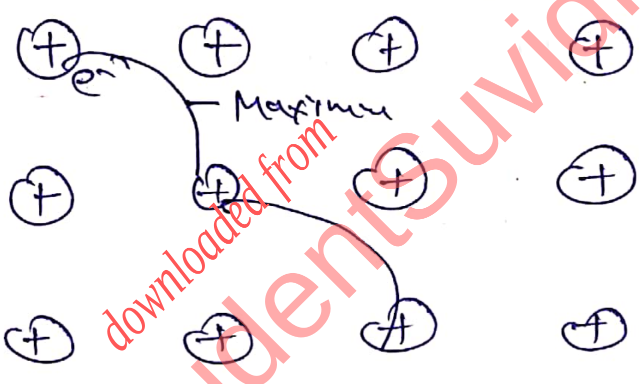
In order to find the allowed energy of electrons in Solids, we must solve the Schrodinger Equation for an electron in ~~Solids~~ a crystal lattice.

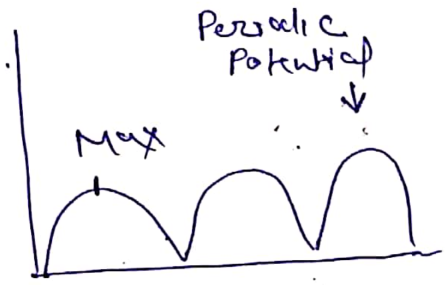
"Kronig & Penney suggested a simplified Model consisting of an infinite row of rectangular Potential well. Each well represent an approximation to the Potential Produce by one ion."

OR

Kronig Penny Model is a simplified model for electron in one Dimensional Periodic Potential.

Let us consider a crystal lattice, let us discuss the variation of Potential Energy in a crystal lattice.



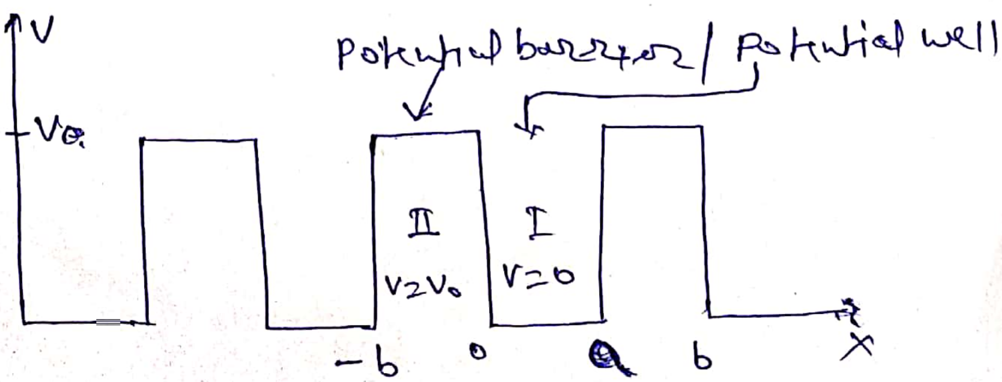



The Highest Potential is halfway between the Atoms.

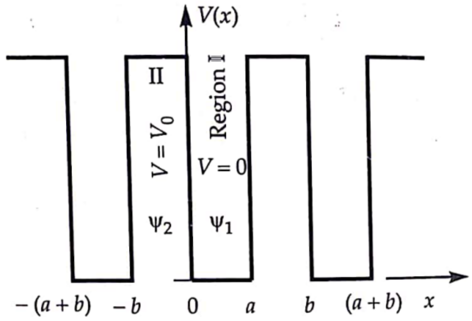
Kronig Penny Consider these Periodic Potential as Rectangular Step.

Potential barrier Potential = Maximum

Potential well Potential = 0



$$\left\{ \begin{array}{lll} V = 0 \ , & 0 < x < a & \text{Region - I} \\ V = V_0 \ , & -b < x < 0 & \text{Region - II} \end{array} \right\}$$




For region I Schrodinger wave Eqn is

$$\frac{d^2\psi}{dx^2} + \frac{8\pi^2 m}{h^2}(E-V)\psi = 0$$

$V = 0$

$$\Rightarrow \frac{d^2\psi}{dx^2} + \frac{8\pi^2 m E\psi}{h^2} = 0 \quad \text{—(1)}$$

For Region-II Schrodinger wave Eqn is-

$$\frac{d^2\psi}{dx^2} + \frac{8\pi^2 m(E-V_0)}{h^2}\psi = 0 \quad \text{—(2)}$$

Let $\alpha^2 = \frac{8\pi^2 mE}{h^2}$ —(3)  $-\frac{8\pi^2 m(E-V_0)}{h^2} = \beta^2$ —(4)

Using (3), (4) in (1) & (2)

$$\frac{d^2\psi}{dx^2} + \alpha^2\psi = 0 \quad \text{—(5)}$$

$$\frac{d^2\psi}{dx^2} - \beta^2\psi = 0 \quad \text{—(6)}$$

Also let $\psi = e^{ikx}u_k(x)$ —(7)

being a periodic function.

Now General solution of Equation (5) & (6) will be-

$$\psi_1(x) = A e^{i(\alpha - k)x} + B e^{-i(\alpha + k x)x} \quad \text{--- (8)}$$

$$\psi_2(x) = C e^{(\beta - ik x)} + D e^{-(\beta + ik)x} \quad \text{--- (9)}$$

Solving the above Equation we get

$$\boxed{\frac{P}{\alpha a} \sin \alpha a + \cos \alpha a = \cos ka} \quad \text{--- (10)}$$

↓

Kronig - Penny Model Equation.

where $P \rightarrow$ Strength with which electrons in a crystal are attracted to the ions on the crystal lattice site

a - Interatomic Distance.

Now CASE - I

when $P = 0$

From (10) $\cos \alpha a = \cos ka$.

$\Rightarrow \alpha a = ka$

$\alpha = k$

$\alpha^2 = k^2$

$$\frac{8\pi^2 mE}{h^2} = \left(\frac{2\pi}{\lambda}\right)^2$$

$$\frac{8\pi^2 mE}{h^2} = \left(\frac{2\pi}{h/p}\right)^2$$

$$\boxed{E = \frac{p^2}{2m}}$$

* value of E indicate that Energy of Electron is kinetic Energy.
* Hence Electron can move Freely
* It indicate Nature of Conductor

CASE - II $P = \infty$

From (10)

$$\frac{\sin \alpha a}{\alpha a} + \frac{\cos \alpha a}{P} = \frac{\cos ka}{P}$$

$\Rightarrow \sin \alpha a = 0$

$\sin \alpha a = \sin n\pi$

$\alpha a = n\pi$

$\alpha^2 = \frac{n^2 \pi^2}{a^2}$

$$\left(\frac{8\pi^2 mE}{h^2}\right) = \frac{n^2 \pi^2}{a^2}$$

$$\boxed{E = \frac{n^2 h^2}{8 m a^2}}$$

* n - order, m - Mass of $e^-$
* This Eqn of Energy is Similar to potential well Equation
* Value of E indicate Potential well.
* Potential well indicate bound electron
* It indicate Nature of Insulator.

Important
Brillouin zones:- 1) In one Dimensional lattice

Volume around the origin covered by Bragg's Plane called Brillouin zones.

(Note:- Bragg's Plane is Perpendicular drawn between two lattice points).

OR

The Electron moving in a Perfect Periodic ~~lattice~~ Potential lattice can have Energy only in the allowed region called zones.

OR

In the k-space (k is Propagation constant), the graph between Energy (E) & k is discontinuous, The volume between these discontinuities is known as Brillouin zones.

These discontinuities in one dimensional lattice occurs when $k = \frac{n\pi}{a}$, where k is Negative or Positive integer.

$$k = \pm\frac{\pi}{a}, \pm\frac{2\pi}{a}, \pm\frac{3\pi}{a}, \pm\frac{4\pi}{a} ---$$

The First reflection and the First Energy gap occurs at $k = \pm\frac{\pi}{a}$ because the wave reflected from one atom in a linear lattice interfer constructively with the Nearest Neighbouring atom,

Then the segment $-\frac{\pi}{a} \leq k < +\frac{\pi}{a}$ calle First Brillouin zone.

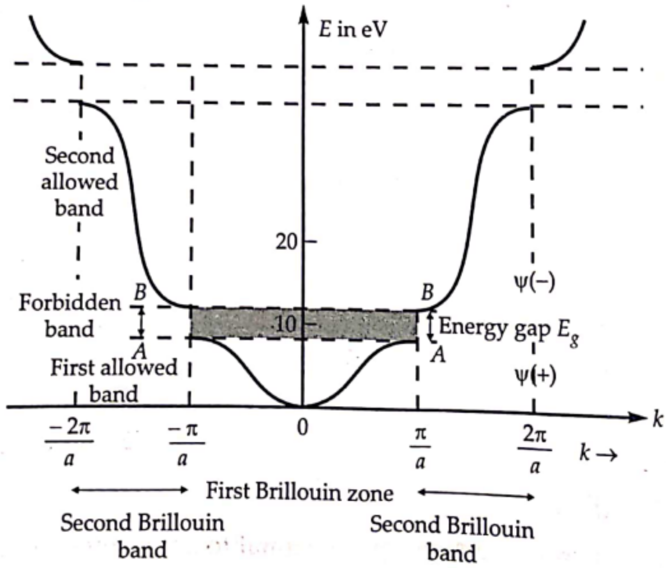
The Second Reflection and second Energy gap occur at $k = \pm\frac{2\pi}{a}$

∴ k Space between $-\frac{2\pi}{a}$ to $-\frac{\pi}{a}$ and $+\frac{\pi}{a}$ to $+\frac{2\pi}{a}$

OR $-\frac{2\pi}{a} \leq k - \frac{\pi}{a}$ and $+\frac{\pi}{a} \leq k \leq +\frac{2\pi}{a}$

Called Second Brillouin zone. —etc

The first and second Brillouin zone and Energy gap are shown by plotting value of E & K as shown below.




The first and second BZ and energy gap.

II) Two Dimensional lattice.

Consider X – Y Plane be the square ABCD.

The boundaries of square is given by –

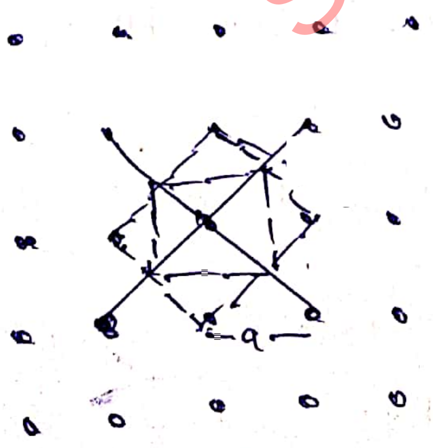
$$k_x = \pm\frac{\pi}{a}, \quad k_y = \pm\frac{\pi}{a}$$

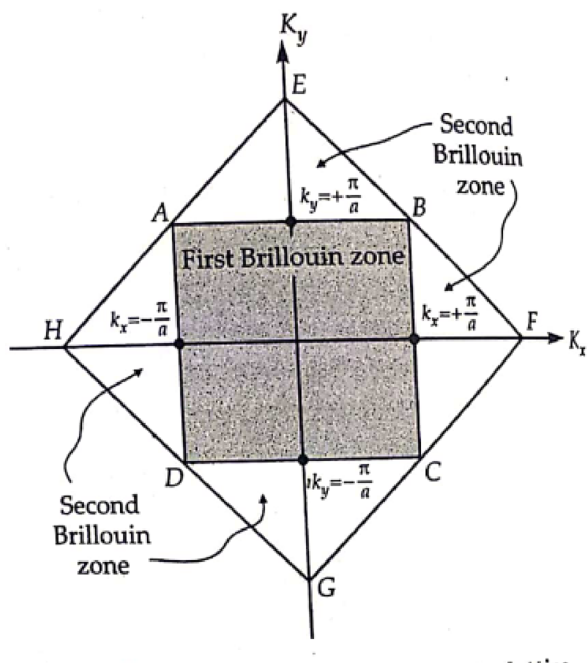
is first Brillouin zone.

Now the boundaries of second square EFGH is given by –

$$k_x = \pm\frac{2\pi}{a}, \quad k_y = \pm\frac{2\pi}{a}.$$

is second Brillouin zone.




First and second BZ in 2D lattice.

# Effective Mass :- * Important

Mass exhibited by an electron when inside the Semi Conductor is called Effective Mass.

OR

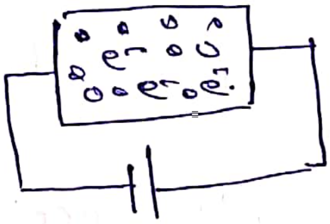
Deviation of electron behaviour in the crystal lattice from free electron behaviour can be taken into account by considering the Electron to have Effective Mass $m^*$.

$$\frac{1}{m^*} = \frac{4\pi^2}{h^2} \frac{d^2E}{dk^2}$$

$m^* \rightarrow$ Effective Mass.

Electron moving inside the Semi Conductor is moving under the influence of atom and other electrons.

Due to this Electrostatic field act on electron known as crystal field. This is called internal Electric field.




This result effective mass of $e^-$ ($m^*$).

**Derivation** :- According to quantum theory $e^-$ moving with velocity $v$ is equivalent to wave packet (group of wave) moving with $v_g$ (group velocity). i.e.

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

Also $E = h\nu = \frac{h}{2\pi} \times 2\pi\nu \Rightarrow \boxed{E = \hbar\omega}$ $-(2)$

Diff (2) wrt k we get.

$$\frac{dE}{dk} = \hbar \frac{d\omega}{dk} \Rightarrow \frac{d\omega}{dk} = \frac{1}{\hbar} \frac{dE}{dk} \quad -(3)$$

Comparing (1) & (3) we get $v = \frac{1}{\hbar} \frac{dE}{dk}$ $-(4)$

Now According to de broglie hypothesis.

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

$$p = \frac{h}{\lambda} \Rightarrow \frac{h}{\lambda} \times \frac{2\pi}{2\pi}$$

$$\Rightarrow p = \frac{h}{2\pi} \times \frac{2\pi}{\lambda} = \hbar k$$

$$p = \hbar k$$

Diff wrt t

$$\frac{dp}{dt} = \hbar \frac{dk}{dt} \Rightarrow F = \hbar \frac{dk}{dt}$$ (By Newton Second Law $F = \frac{dp}{dt}$).

$$\Rightarrow \hbar \frac{dk}{dt} = F = eE \quad -(5)$$

By (4) Now Diff (4) wrt t we get.

$$v = \frac{1}{\hbar} \frac{dE}{dk} \Rightarrow \frac{dv}{dt} = \frac{1}{\hbar} \frac{d^2E}{dk^2} \frac{dk}{dt} \quad -(6)$$

from (5) $\frac{dk}{dt} = \frac{F}{\hbar}$

Also Acceleration $a = \frac{dv}{dt}$

from (6) $a = \frac{1}{\hbar} \frac{d^2E}{dk^2} \frac{dk}{dt}$

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

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

Taking $a/F = m^*$ we get

$$\boxed{m^* = \frac{1}{\hbar} \frac{d^2E}{dk^2}} \quad \text{— Effective Mass.}$$

If $m^* = m$ then electron in crystal belongs a free electron.

*Example 6.3* *The energy near the valence band edge of a crystal is given by* $E = -10^{-39} k^2 \, Jm^2$. *An electron with wave vector* $10^{10} \hat{k}_x \; m^{-1}$ *is removed from an orbital in the completely filled valence band. Determine effective mass and momentum.*

**Solution.** Given : $E = -10^{-39} k^2$ . Hence $\frac{d^2 E}{dk^2} = -2 \times 10^{-39}$

Effective mass of the electron

$$m^* = \hbar^2 / \frac{\partial^2 E}{\partial k^2} = -\frac{(1.05 \times 10^{-34})^2}{2 \times 10^{-39}} = -5.5 \times 10^{-30} \text{ kg}$$

Momentum of electron $= \hbar k = 1.05 \times 10^{-34} \times 10^{10} \hat{k}_x = 1.05 \times 10^{-24} \hat{k}_x \; \text{Js m}^{-1}$.

## Comparison between Ordinary Diode and Zener Diode

| S.No. | Ordinary Diode | Zener Diode |
|---|---|---|
| 1. | Ordinary diode is operated in forward biased condition. | Zener diode is always operated in reverse biased condition. |
| 2. | It utilizes the forward characteristics. | It utilizes, the reverse characteristics. In forward bias it acts like a *PN* junction diode. |
| 3. | It does not have any sharp breakdown voltage. | If property doped, it has a sharp breakdown $V_Z$. |

## Fermi level :-

The Maximum Energy that electron may posses at 0K is the Fermi Energy ($E_F$).

" Fermi level is the surface of the sea of electron at Absolute zero, where no electron will have enough energy to rise above the surface."

Now in order to know how many of Electronic Energy State in the valence band and conduction band will be occupied at different temperature Fermi factor f(E) is introduce as -

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

where $k_B$ - Boltzmann constant

T - Temperature in K

$E_F$ - Fermi level of Energy in eV.

E - Given energy occupied by Electron under condition of thermal Equilibrium.

Now

I) $E > E_F$ & $T=0$ $\quad f(E) = \frac{1}{1+\exp(\infty)} = 0$

II) $E < E_F$ & $T=0$ $\quad f(E) = \frac{1}{1+\exp(-\infty)} = 1$

III) $T = TK$ and $E = E_F$

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

which means when temperature is not

which means when temperature is not 0°
0K but some higher value say T=1000K
then some ~~electrons~~ covalent bond will
break and some electron will transfer to
conduction band.

**Example 6.7** *Fermi energy of an intrinsic semiconductor is 0.6 eV. The low lying energy level in the conduction band is 0.2 eV above the Fermi level. Calculate the probability of occupation of this level by an electron at room temperature.*

***Solution.*** Given $E_F = 0.6$ eV, then $E = (0.6+0.2)$ eV $= 0.8$ eV

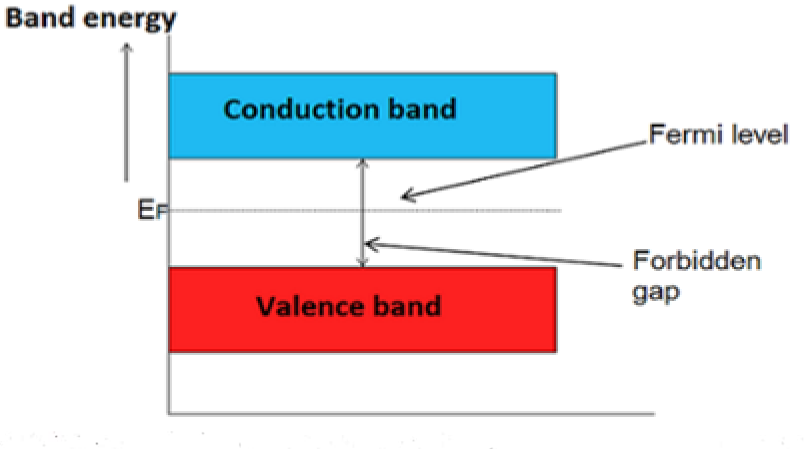
The probability of occupation of an energy level by an electron is given by the F-D distribution law

$$f(E) = \frac{1}{1+\exp\frac{E-E_F}{k_BT}} = \frac{1}{1+\exp\frac{(0.8-0.6)\,\text{eV}\times 1.6\times 10^{-19}\,\text{J}}{1.38\times 10^{-23}\,\text{JK}^{-1}\times 300\,\text{K}}}$$

$$= \frac{1}{1+\exp 7.7} = 0.0004 = 0.04\ \%$$

## Fermi level in Intrinsic Semiconductor:-

* In Intrinsic or pure semiconductor, the number of holes in valence band is equal to number of electrons in conduction band.
* The probability of occupation of energy levels in conduction band and valence band are equal.
* Fermi level for intrinsic semiconductor lies in the middle of forbidden band.



Fermi level for intrinsic semiconductor is given as-

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

where $E_F$ — Fermi level

$E_C$ - Conduction band.

$E_V$ - valence band.

## Fermi level in extrinsic semiconductor:-

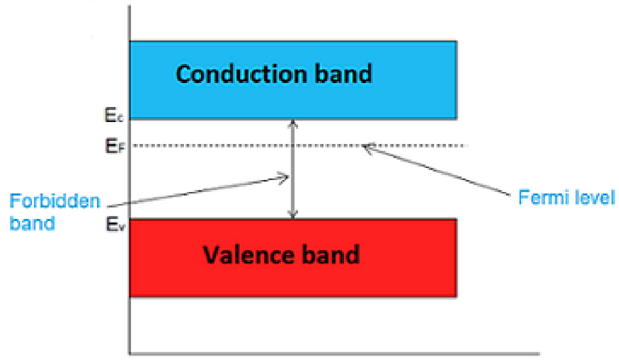
* In extrinsic semiconductor, the number of electron in conduction band and number of holes in valence band are not equal.
* Hence, the probability of occupation of energy in conduction band and valence band are not equal.
* Fermi level for extrinsic semiconductor lies close to the conduction or valence band.

## 1) Fermi level in n-type semiconductor:-

* At room temperature, the number of electrons in conduction band is greater than number of holes in valence band.
* Probability of occupation of energy levels by electron in the conduction band is greater than the Probability of occupation of energy levels by holes in valence band.
* Therefore the Fermi level in n-type semiconductor lies close to conduction band.

Fermi level for n-type Semiconductor is given as -

$$E_F = E_C - k_B T \log \frac{N_C}{N_D}$$




$E_F$ - Fermi level

$E_C$ - Conduction band

$k_B$ - Boltzmann Constant

T - Absolute Temperature

$N_C$ - Effective density of State in CB

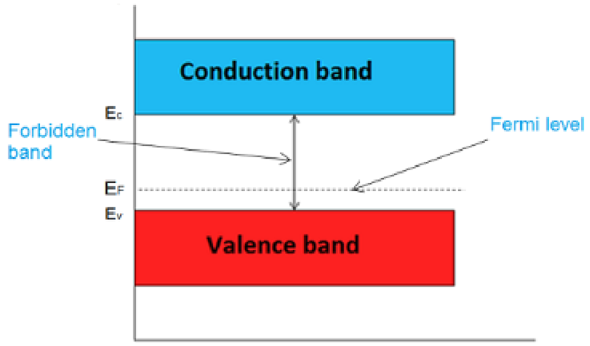
$N_D$ - Concentration of Doner atom.

## Fermi level in P-type Semiconductor:-

* Number of holes in valence band is greater than the number of electron in conduction band.

* Probability of occupation of Energy levels by the holes in the valence band is greater than the probability of occupation of Energy level in the conduction band.

* Therefore the Fermi level in P-type Semiconductor lies close to valence band.



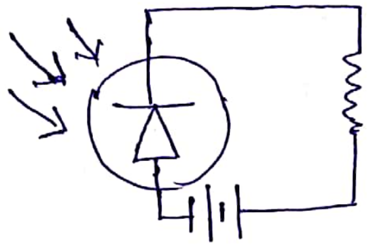

The Fermi level for P-type Semiconductor is given as-

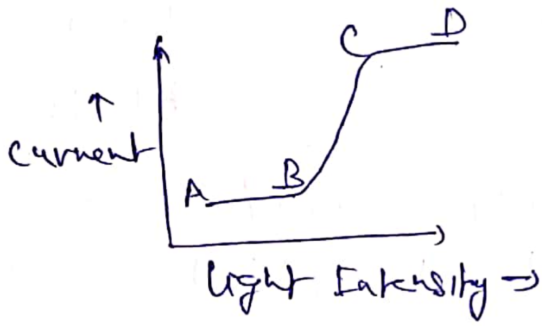
$$E_F = E_V + k_B T \log \frac{N_V}{N_A}$$

$N_V$ - effective density of State in VB

$N_A$ - Concentration of Acceptor ion.

**Photo diode:→** A photodiode is a p-n junction diode, made from photosensitive semi conducting material, whose conductivity is controlled by light falling on it.






In can work in two form Photodetector as well as solar cell.

Basically Photodiode is a P-n junction diode designed to respond under Photon absorption. There will be Absorption only if $h\nu > E_g$

**LED:→** (Light Emitting Diode)

LED is forward bias P-n junction diode.

If we apply forward bias then. Electron Hole Pair recombine near the junction, hence recombination energy emitted in the form of Photon of Energy $h\nu = E_g$

→ Here we use direct band gap semi conductor such that most of light must be emitted in the form of Photon. Energy of Photon depends on the bandgap of semi conductor.

$$E_g = h\nu$$

$$E_g = \frac{hc}{\lambda} = \frac{1240}{\lambda\,(nm)}\ eV$$

* LED emit incoherent light.

## Parameters of LED:-

I) **Quantum Efficiency of LED:-** It is defined as

$$Q.E = \frac{\text{optical power out}}{\text{Electrical power in}} \leq 1$$

Q.E ($\eta$) = 80% means 80% of electrical power convert into optical power.

Here power is Energy per second

E.E Energy/(per sec) = $nh\nu$

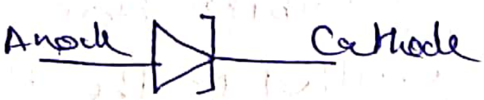
n → no. of photons per sec.

By this formula we can calculate no. of photons/sec

II) **Slope Efficiency:-** It is defined as optical power out divided by input current.

$$\text{Slope efficiency} = \frac{\text{Optical Power out}}{\text{Input Current}} \left(\frac{W}{A}\right)$$

**Tunnel Diode:-** A tunnel diode is a heavily doped PN junction diode




→ Tunnel Diode shows negative resistance, so it can be used as amplifier, oscillators and in any switching circuits.

→ When voltage value increase, current flow decrease

→ Tunnel Diode is based on tunnel Effect

→ Heavily doped P-type & n-type semiconductor in tunnel diode results in a narrow depletion region.