



# Energy band structure in semiconductors

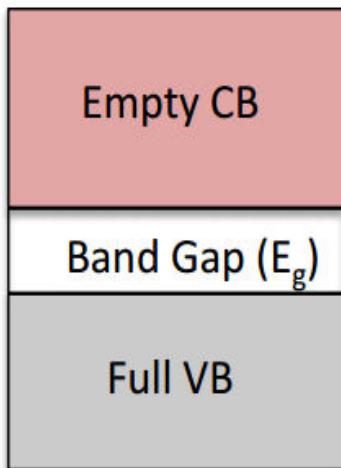
**In a semiconductors, At 0K,**

- The lower energy bands are completely filled.
- The higher energy bands are completely empty.
- The nearly upper filled band is called the valence band.
- The nearly lowest empty band is called the conduction band.
- The gap between valence band and conduction band is called the band gap.
- The totally filled band and unfilled band do not conduct current.
- The uppermost filled and lowermost unfilled only conduct current in a semiconductor.

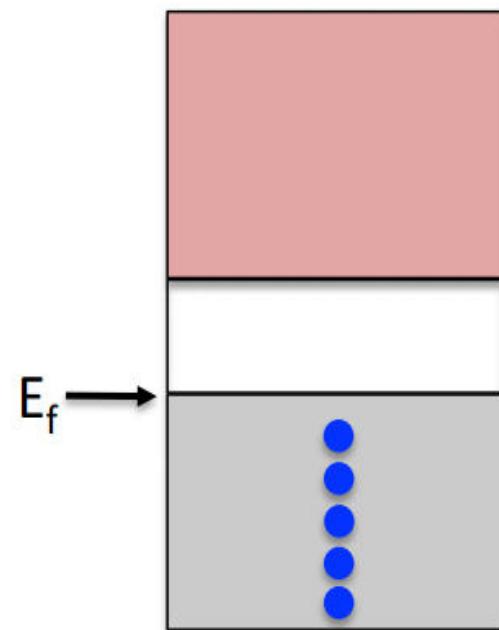


# Energy band structure in semiconductors

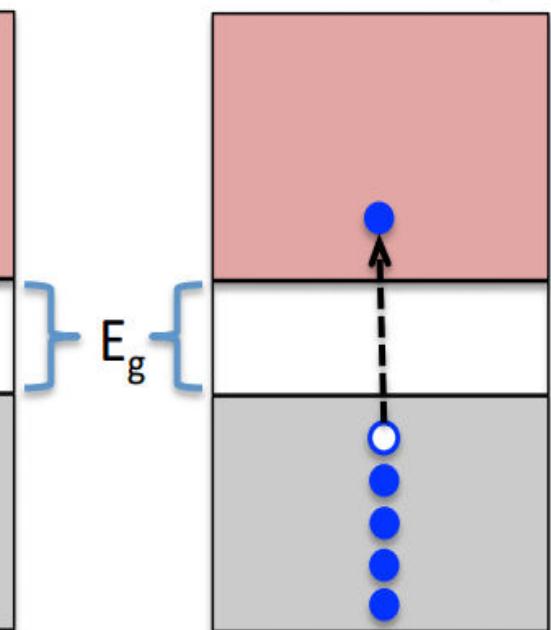
Energy Band  
Diagram at 0K



0 Kelvin



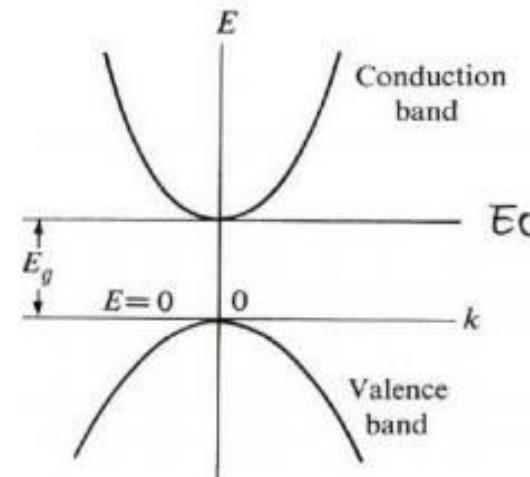
Room Temp





# Band Gaps in Semiconductors

Energy Band Diagram at 0K

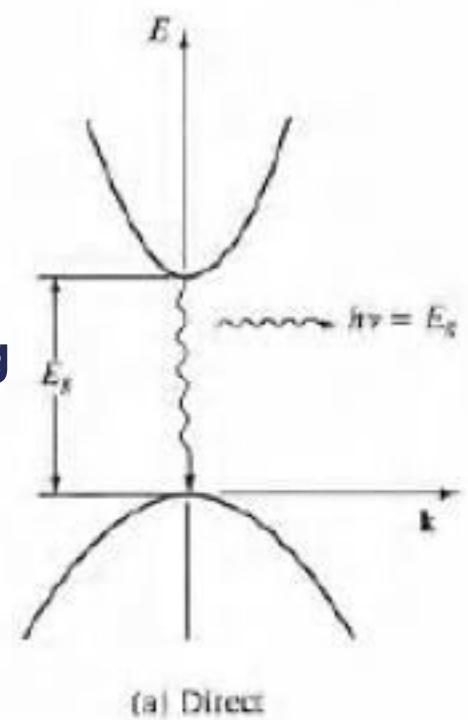


- Based on the Band gap, semiconductors are classified into
- **Direct band gap semiconductors**
  - **Indirect band gap semiconductors**



# Direct Band Gap Semiconductors

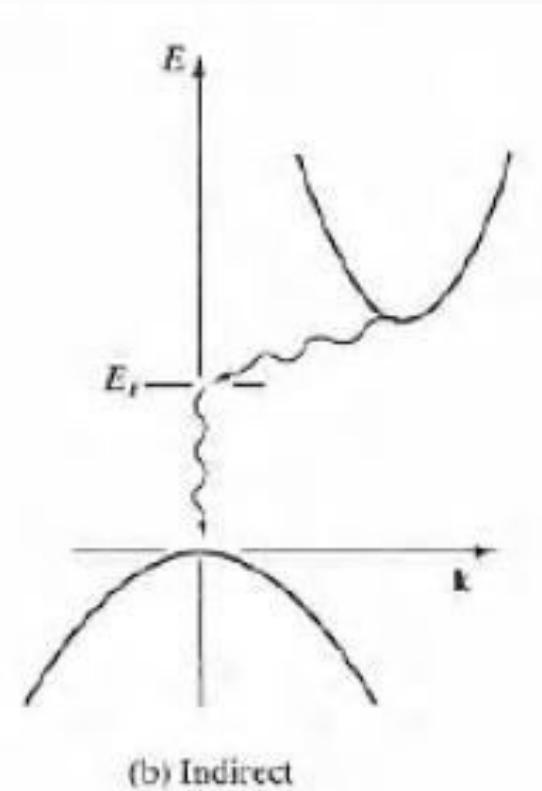
- The conduction band minima and the valence band maxima occurs at the same value of momentum.
- An electron from the conduction band returns to the valence band without changing its momentum and releases energy in the form of light (photons).
- These direct band gap materials are the efficient sources of light such as LEDs, Lasers etc.





# Indirect Band Gap Semiconductors

- The conduction band minima and valence band maxima occurs at different momentum.
- The electrons from the conduction band returns to the valence band with varying momentum and releases energy in the form of heat (phonons).
- These indirect band gap materials are more efficient for making diodes, transistors etc.
- Example: Silicon, Germanium.





## Importance of Direct & Indirect Band Gap Semiconductors

The difference between direct and indirect band structure is very important for deciding which semiconductors can be used in devices requiring light output.



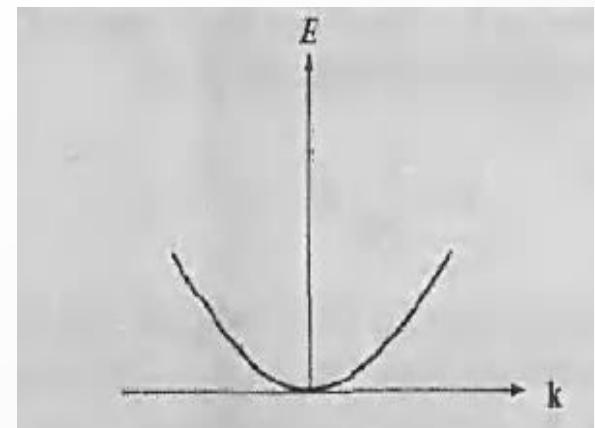
## Effective Mass in Semiconductors

The E-K relationship for the free electron is calculated and is related to the electron mass.

The electron momentum is  $p = mv = \hbar k$ . Then

$$E = \frac{1}{2}mv^2 = \frac{1}{2}\frac{p^2}{m} = \frac{\hbar^2}{2m}k^2$$

Thus the electron energy is parabolic with wave vector K.





## Effective Mass in Semiconductors

When an electron is moving inside the solid material the potential field will affect the movement of electron. For low kinetic energy,

$$E = P / 2m^*$$

Where  $P$  is the crystal momentum.

i.e. a conduction electron behaves as a particle with an effective mass  $m^*$ .

The effective mass of an electron ( $m^*$ ) in a band is given as

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

- $m^*$  reflects the periodic potential and the motion of an electron.
- $m^*$  is inversely proportional to the second derivative of E – K diagram.



## Effective Mass in Semiconductors

For a free electron if  $m^* = m$ , the conduction band energy of an electron in K-space is given as,

$$E = \frac{\hbar^2}{2m^*}k^2 + E_c$$

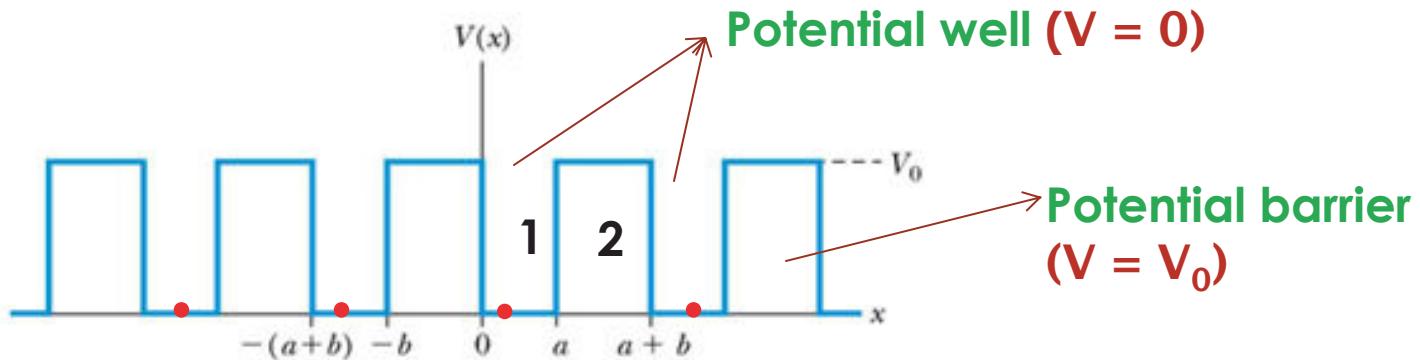
If this is compared with  $m^*$ , it shows that the effective mass is constant in the parabolic band.

Hence the conduction band effective mass is directly related to the band gap energy. i.e. if the band gap is small then the effective mass is also small. Hence the effective mass of an electron differs from band to band and also depends on the nature of the bond.



## Kronig - Penny Model

- The Kronig-Penney model demonstrates that a simple one-dimensional periodic potential yields energy bands as well as energy band gaps.
- The potential assumed is shown as below



- represents the positive ion core

In the **potential well** near the positive ion electron potential is zero i.e.  $V = 0$

In the **potential barrier** away from the positive ion electron potential is maximum i.e.  $V = V_0$



## Kronig - Penny Model

According to this theory, the electrons move in a periodic potential produced by the positive ion cores. The potential of the electron varies periodically with periodicity of the ion core and the potential energy of the electron is zero near the nucleus of the positive ion core and maximum when it is lying between the adjacent nuclei which are separated by the interatomic spacing ' $a$ '.



## Kronig - Penny Model

Applying the Schrodinger's Time Independent wave equation for the above two regions,

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

for I in the diagram,  $V=0$

$$\frac{d^2\psi}{dx^2} + \frac{2mE}{\hbar^2} \psi = 0 \rightarrow ① \quad \text{for } 0 < x < a$$

for II in the diagram,  $V=V_0$

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} (E-V_0) \psi = 0 \rightarrow ② \quad \text{for } -b < x < 0$$

$$\text{Put } \alpha^2 = \frac{2mE}{\hbar^2}, \beta^2 = -\frac{2m}{\hbar^2} (E-V_0)$$



## Kronig - Penny Model

Substituting the value of  $\alpha$  and  $\beta$ ,

Then equations ① and ② becomes

$$\frac{d^2\psi}{dx^2} + \alpha^2\psi = 0 \rightarrow ③$$

$$\frac{d^2\psi}{dx^2} - \beta^2\psi = 0 \rightarrow ④$$

The solutions for Equations 3 and 4 can be given as,

$$\psi = e^{ikx} u_k(x) \rightarrow ⑤$$



## Kronig - Penny Model

differentiating ⑤ with respect to 'x'

$$\frac{d\psi}{dx} = \frac{d}{dx} e^{ikx} u_k(x)$$

$$\frac{d^2\psi}{dx^2} = e^{ikx} \frac{d}{dx} u_k(x) + u_k(x) \frac{d}{dx} e^{ikx}$$

$$\frac{d^2\psi}{dx^2} = e^{ikx} \cdot \frac{du_k}{dx} + u_k i k e^{ikx}$$

Again differentiating with respect to 'x'

$$\frac{d^3\psi}{dx^3} = e^{ikx} \cdot \frac{d^2 u_k}{dx^2} + \frac{du_k}{dx} (i k e^{ikx}) + i k \left[ u_k i k e^{ikx} + e^{ikx} \frac{du_k}{dx} \right]$$

$$\frac{d^3\psi}{dx^3} = e^{ikx} \frac{d^2 u_k}{dx^2} + i k e^{ikx} \frac{du_k}{dx} - k^2 u_k e^{ikx} + i k e^{ikx} \frac{du_k}{dx} \rightarrow ⑥$$



## Kronig - Penny Model

Put equ@ in equ ③

$$e^{ikx} \frac{d^2 U_k}{dx^2} + ik e^{ikx} \frac{dU_k}{dx} - k^2 U_k e^{ikx} + ik e^{ikx} \frac{dU_k}{dx} + \alpha^2 e^{ikx} U_k = 0$$

Divide the above equation with  $e^{ikx}$

$$\frac{d^2 U_k}{dx^2} + ik \frac{dU_k}{dx} - k^2 U_k + ik \frac{dU_k}{dx} + \alpha^2 U_k = 0$$

$$\frac{d^2 U_k}{dx^2} + 2ik \frac{dU_k}{dx} + (\alpha^2 - k^2) U_k = 0 \rightarrow ⑦$$

Put equ @ in ④ , we get

$$\frac{d^2 U_k}{dx^2} + 2ik \frac{dU_k}{dx} - (\beta^2 + k^2) U_k = 0 \rightarrow ③$$



## Kronig - Penny Model

The general solution for equations 7 & 8 can be given as,

$$U_1 = Ae^{i(\alpha-k)x} + Be^{-i(\alpha+k)x} \rightarrow ⑨$$

$$U_2 = Ce^{(\beta-i\kappa)x} + De^{-(\beta+i\kappa)x} \rightarrow ⑩$$

By solving above two equations , we get

$$\alpha + \beta = C + D$$

And solving the above equation at boundary conditions,

We get  $\frac{\alpha^2 + \beta^2}{\alpha\beta} \sinh\beta b \sin\alpha a + \cosh\beta b \cos\alpha a = \cos k(a+b)$

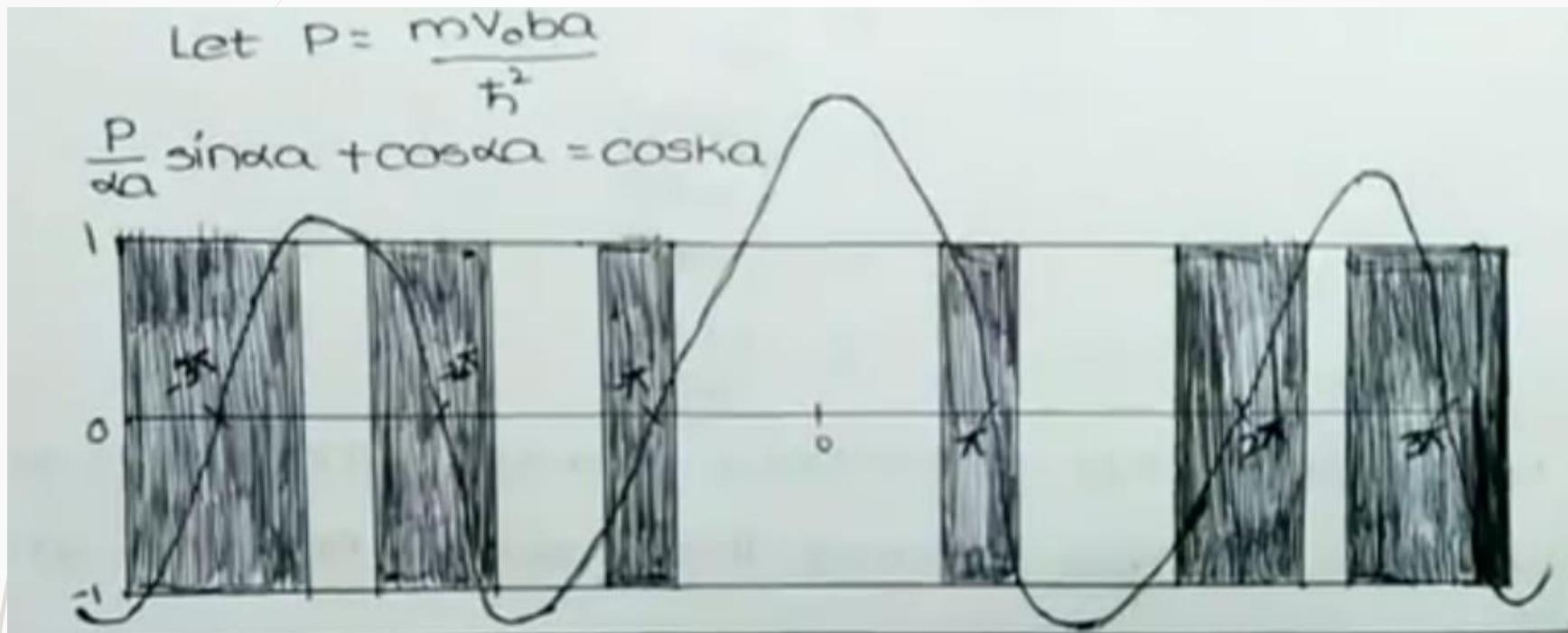
By solving we get,

$$\frac{mv_0b}{\alpha\hbar^2} \sin\alpha a + \cos\alpha a = \cos ka$$

$$\frac{mv_0ba}{\alpha a\hbar^2} \sin\alpha a + \cos\alpha a = \cos ka$$



## Kronig - Penny Model



- Shaded region represents the **Allowed Region** (-1 to +1)
- Non - Shaded region represents the **Forbidden Region**
- The discontinuity in energy occurs at the region at  $K = \pm \pi/a, \pm 2\pi/a, \pm 3\pi/a...$



## Discussion

➤ At P tends to infinity,  $\sin \alpha a = 0$ , i.e.  $\alpha a = n\pi$ ,  $\alpha = n\pi/a$ .

$$\text{Hence Energy } E = n^2\pi^2 / 8ma^2$$

In this case, the Energy levels are discrete

It is similar to a particle in a one dimensional potential box.

This indicates the nature of an insulator.

➤ At P tends to Zero,  $\cos \alpha a = \cos Ka$ ,

$$\text{Hence Energy } E = P^2 / 2m$$

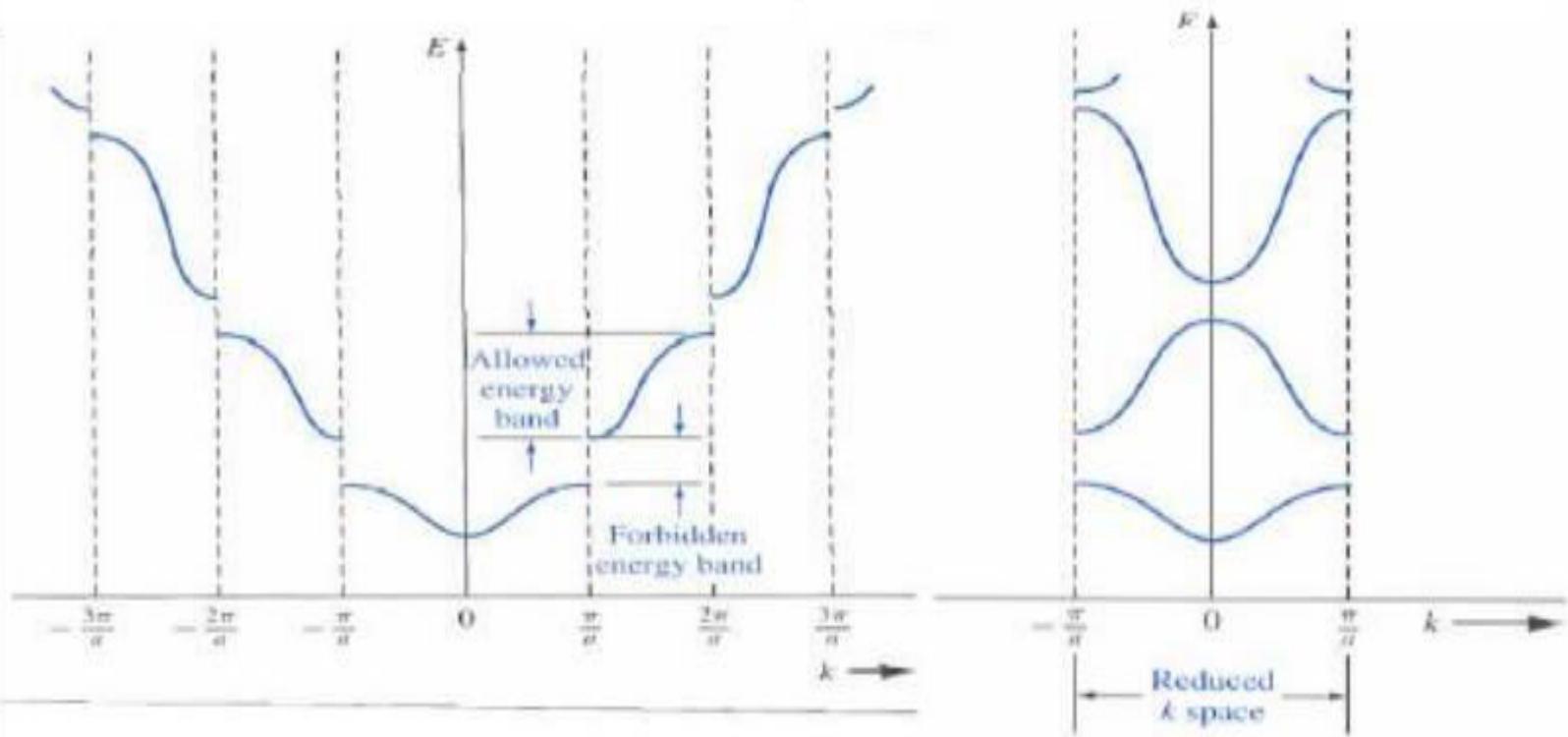
In this case, the Energy of an electron is Kinetic, shows it is a free electron.

This indicates the nature of a conductor.



# E-K Diagram

E-K Diagram in Kronig-Penney Model





## E-K Diagram Discussion

- All real K vectors lead to propagate electron states, results to allowed states.
- All imaginary K vectors cannot propagate electron states, results to forbidden states.
- If the potential barrier between the walls is strong, energy bands are narrow and wide apart.
- If the potential barrier is weak, energy bands are wide and closely packed.

## 2. DETERMINATION OF BAND GAP OF A SEMICONDUCTING MATERIAL

Expt. No:

Date:  /  /

### AIM

To determine the band gap of a given semiconducting material.

### APPARATUS REQUIRED

1. A kit provided with a dc power supply (0 - 5V), a voltmeter, a micro-ammeter and connecting terminals
2. A given semiconductor diode
3. A water or oil bath with heating arrangement
4. A thermometer
5. Connecting wires

### FORMULA

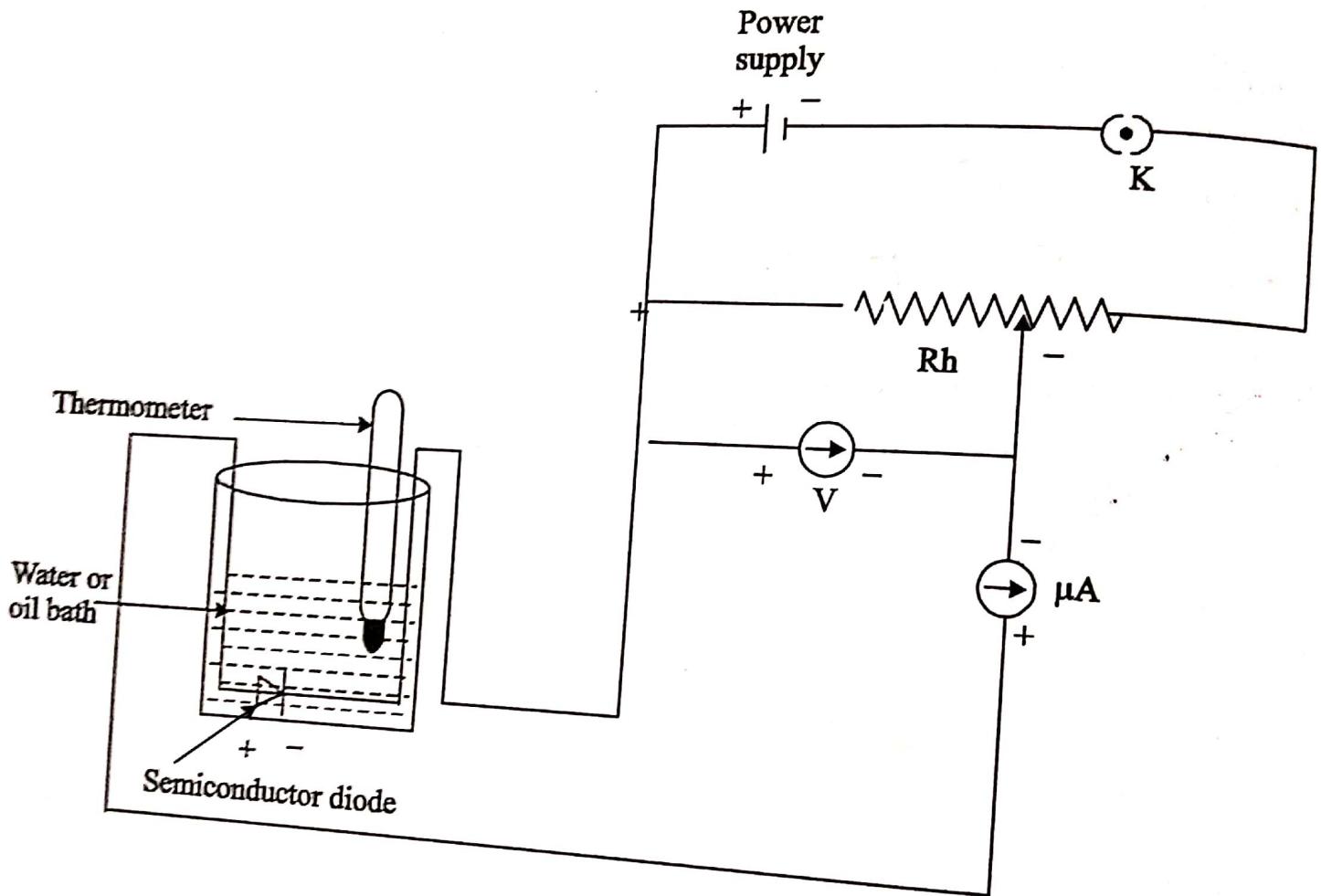
The band gap of the given semiconducting material,

$$E_g = 0.198 \times \text{slope of the plot of } \log I_s \text{ versus } \frac{10^3}{T} \text{ eV}$$

### PROCEDURE

The connections are made wires as shown in Fig. The given semiconductor is immersed in a water or oil bath. The semiconductor diode is reverse biased by connecting the positive side of the power supply to the negative terminal and the negative side of the power supply to the positive terminal of the diode. A thermometer is placed in the water/oil bath to measure the temperature of the semiconductor diode.

The water/oil bath is heated using a heater up to the temperature 75°C. The heater is switched off. The DC power supply is switched on and the knob is adjusted to have any value between 0.5 V and 2.0 V in the voltmeter depending upon the type of semiconducting material. When the water/oil bath cools to the temperature 70°C the microammeter reading is noted. The microammeter reading is called reverse saturation current  $I_s$ . The microammeter readings are noted when the temperature of the water/oil bath cools to the temperature 65°C, 60°C, 55°C, 50°C successively and the readings are tabulated. A graph is drawn taking  $\log I_s$  along Y-axis and  $\frac{10^3}{T}$  along X-axis. The plot will be a straight



**Fig. Band gap determination - circuit diagram**

line as explained below. The following equation shows the variation of reverse saturation current ( $I_s$ ) with respect to temperature ( $T$ ).

$$I_s = A \exp\left(\frac{-E_g}{kT}\right)$$

where  $A$  is a constant,  $E_g$  is the band gap of the semiconducting material and  $k$  is Boltzmann constant.

Taking logarithms on both sides,

$$\ln I_s = \ln A - \frac{E_g}{kT}$$

or  $2.303 \log I_s = 2.303 \log A - \frac{E_g}{kT}$

Dividing throughout by 2.303

$$\log I_s = \log A - \frac{E_g}{2.303 kT}$$

The gap between valence band and conduction band of a semiconducting material is known as band gap ( $E_g$ ) and it is expressed in eV. Since  $k = 1.38 \times 10^{-23} \text{ J/K}$ , its value is to be divided by electronic charge  $e (= 1.6 \times 10^{-19} \text{ coulomb})$  to convert the unit J/K into eV/K.

$$\log I_s = \log A - \frac{\frac{E_g}{2.303 \times 1.38 \times 10^{-23} \times T}}{1.6 \times 10^{-19}}$$

$$\log I_s = \log A - \frac{E_g \times \left(\frac{10^3}{T}\right)}{0.198}$$

The above relation shows that the graph between  $\log I_s$  and  $\frac{10^3}{T}$  is a straight line.

Hence, the slope of the straight line =  $\frac{E_g}{0.198}$

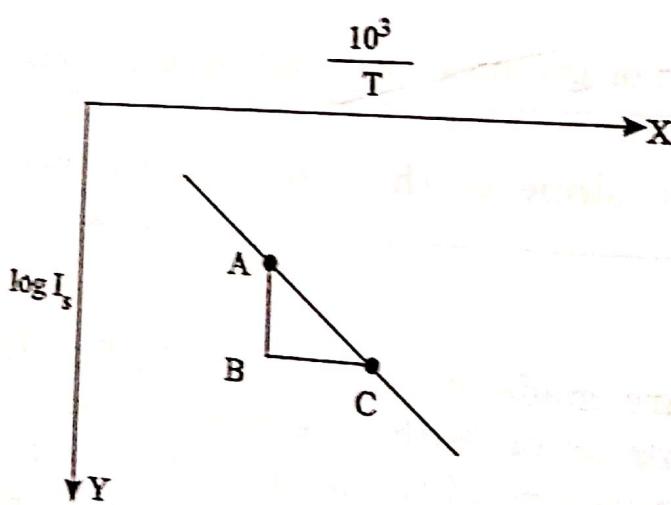
$$\therefore E_g = 0.198 \times \text{slope of the straight line}$$

The band gap is thus determined by calculating the slope of the straight line.

Result: The band gap of the given semiconducting material = \_\_\_\_\_ eV

## (i) Observations

Sl.No.	Temperature of water/oil bath	Temperature of water/oil bath (°C + 273) = T	$\frac{10^3}{T}$	$I_s \times 10^{-6} \text{ A}$	$\log(I_s)$
Unit	°C	K	$\text{K}^{-1}$	$\times 10^{-6} \text{ A}$	
1.	35	308	3.275	48.5	-1.3142
2.	32	302	3.303	49.2	-1.3230
3.	28	291	3.438	49.5	-1.3169
4.	27	290	3.459	49.5	-1.3169
5.	26	289	3.465	49.7	-1.3169
6.	25	284	3.571	49.8	-1.3169
7.	24	277	3.621	49	-1.3169

(ii) A graph between  $\frac{10^3}{T}$  and  $\log I_s$ 

$$\text{Slope} = \frac{AB}{BC} =$$

8.1.23

34

## PROCEDURE

Before starting the experiment, the least count of the microscope is first determined. The given light beam (metre scale) is placed symmetrically over the two knife edge supports A and B so that equal length is projected beyond each knife edge. The distance between the knife edges is measured as  $l$  metre using a metre scale. A pin is fixed vertically at the midpoint of the beam so that the tip of the pin is pointing vertically upwards. There are two weight hangers ( $W, W$ ), each one suspended symmetrically from the beam at equal distance from the nearby knife edge near each end of the beam as shown in Fig. The distance between the point where the weight hanger is suspended and the nearby knife edge is measured as 'a' metre. The beam is loaded by adding weights to each weight hanger in steps of 50 g up to a maximum load. The beam is unloaded by removing weights from the weight hanger in steps of 50 g up to the weight hanger load. The loading and unloading of the beam are done three times so that the beam is brought to elastic mood.

With the weight hangers ( $W, W$ ) suspended from each end of the beam, the tip of the pin is focussed by a microscope to find the elevation of the midpoint of the beam. The fine adjustment screw at the top of the vertical scale is adjusted so that the image of the tip of the pin coincides with the horizontal cross-wire. The Main Scale Reading (MSR) and the corresponding Vernier Scale Coincidence (VSC) are noted in the vertical scale. The Total Reading (TR) is  $(MSR + VSR)$  cm where  $VSR = VSC \times LC$ . The beam is then loaded by adding weights in steps of 50 g to each weight hanger up to a maximum load and the microscope is adjusted each time such that the image of the tip of the pin coincides with horizontal cross-wire. The microscope readings are recorded by observing MSR and VSC for each load. The observations are repeated for decreasing loads also. From the observations, the elevation ( $y$ ) of the midpoint of the beam for a particular load  $M$  (200 g) is calculated and the mean value of  $y$  is determined as shown in the tabular column. The breadth ( $b$ ) and the thickness ( $d$ ) of the beam are measured using Vernier calipers and screw gauge respectively. The Young's modulus of the material of the beam is calculated using the formula.

## RESULT

The Young's modulus of the material of the given beam =

$$= \dots \times 10^{10} \text{ Nm}^{-2}$$



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(Declared as Deemed - to - be - University under section 3 of UGC Act 1956)



# **SEMICONDUCTOR PHYSICS**

## **UNIT - I**

**PRESENTED BY**  
**DR. C. RATHIKA THAYA KUMARI,**  
Associate Professor,  
Department of Physics

# INTRODUCTION



- The electron theory aims to explain the structure and properties of solids through their electronic structure.
- According to this theory a metal can be considered to consist of ion cores having the nucleus and electrons other than valence electrons.
- These valence electrons form an electron gas surround the ion cores and are free to move anywhere within the metals.



- The electron theory of solids has been developed in three main stages

1) **Classical free electron theory**: Drude and Lorentz developed this theory in 1900 . According to this theory metal containing free electron obey the laws of classical mechanics.

2) **Quantum free electron theory**: Sommerfeld developed this theory during 1928. According to this theory, the free electrons obey quantum laws.

### **iii). The Zone theory:**

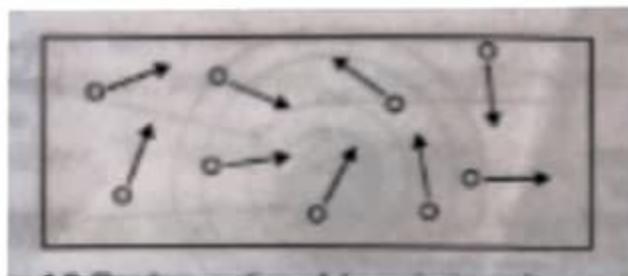
Bloch stated this theory in 1928. According to this theory, the free electrons move in a periodic field provided by the lattice. This theory is also called “Band theory of solids”.



# CLASSICAL FREE ELECTRON THEORY

## POSTULATES

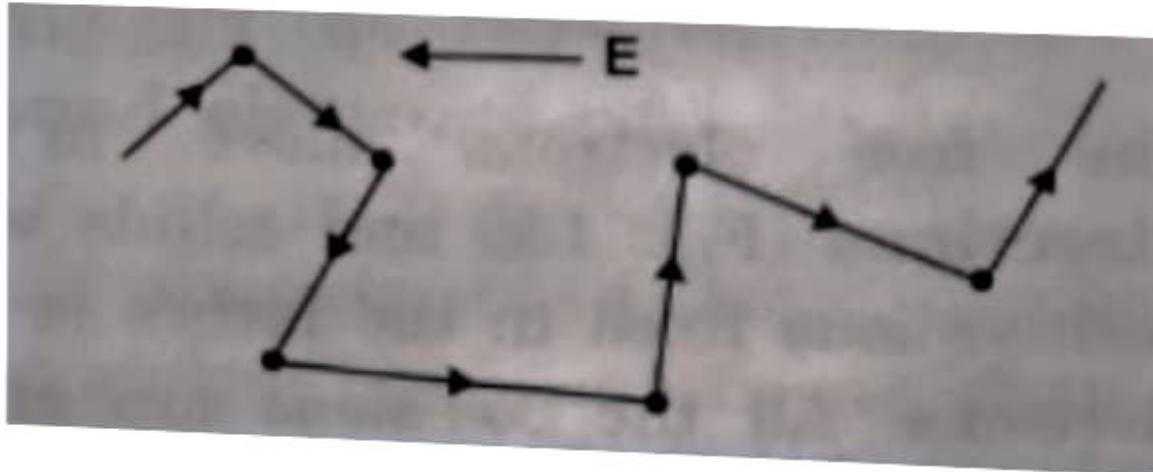
- The free electrons in metals, move freely or randomly in all possible directions, in the absence of electric field



- While moving, the free electrons collide with each other and also with the lattice elastically without any loss in energy.
- The force between electrons and ion core is negligible, hence its total energy is only kinetic not potential.

## **POSTULATES**

- When an external field is applied, the free electrons moves in a direction opposite to the electric field.
- As a result, these free electrons may acquire a constant velocity called drift velocity.





## DEFINITIONS

### DRIFT VELOCITY

The average velocity acquired by the free electron in a particular direction, due to the application of electric field is called drift velocity.

### MOBILITY

The drift velocity acquired by the free electron per unit electric field applied to it.

$$\text{Mobility} = \text{Drift velocity} / \text{Electric field}$$

## **DEFINITIONS**

### **RELAXATION TIME**

**It is the time taken by the free electrons to reach its equilibrium position from its disturbed position in the presence of electric field.**

### **MEAN FREE PATH**

**The average distance travelled between two successive collisions are called mean free path.**



## **DRAWBACKS OF CLASSICAL FREE ELECTRON THEORY**

- It is a macroscopic theory
- Classical theory states that all free electrons absorb energy, but quantum theory states that only few electrons absorb energy.
- Classical theory cannot explain compton effect, photoelectric effect, blackbody radiation etc. but these concepts are completely based on quantum theory.
- The electrical conductivity and resistivity of a semiconductors and insulators are not explained by classical theory but band theory clearly explains these concepts successfully for all solids.



## QUANTUM FREE ELECTRON THEORY

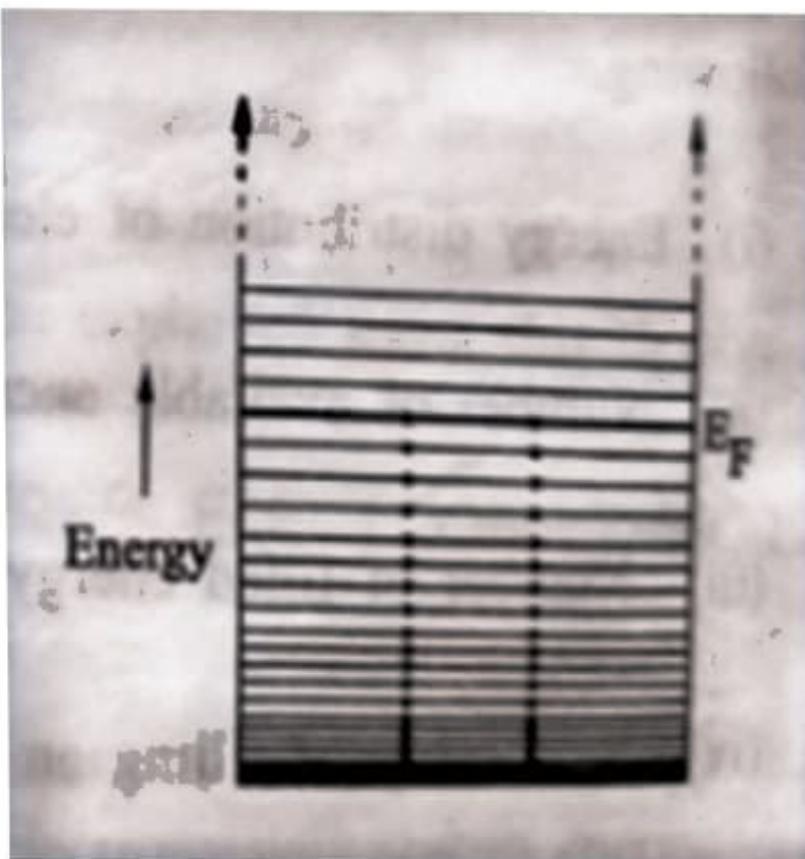
The drawbacks of classical theory can be rectified using quantum theory. The problem was approached using Fermi-Dirac statistics.

### ASSUMPTIONS

- Classical theory – Kinetic Energy of an electron is Zero at 0K.
- Quantum theory – The electrons arrangement in an energy level is clearly explained by knowing the following terms:
  - Energy distribution of an electron
  - Number of available energy states
  - Number of filled energy states
  - Probability of filling an electron in an energy state

## ENERGY DISTRIBUTION OF ELECTRONS IN A METAL

- The energy levels are discrete.
- The space between two energy levels is very less ( $10^{-6}$  eV).
- The distribution of energy levels seems to be continuous.
- Each energy level can provide only two states, one for spin up and the other for spin down.
- Thus 2 electrons can be filled in each energy state.
- If there N number of electrons means,  $N/2$  number of energy states.
- This  $(N/2)$ th level is the highest filled energy level, called Fermi Energy Level.





## **FERMI ENERGY AND ITS IMPORTANCE**

- Fermi energy level is the maximum energy level upto which the electrons can be filled at 0K.
- Thus, it acts as a reference level which separates the vacant and filled states at 0K.
- At 0K, below fermi energy level electrons are filled and above that it is empty.
- When the temperature is increased, few electrons gain thermal energy and it goes to higher energy states.



## FERMI DISTRIBUTION FUNCTION

The probability of an electron occupying in a given energy state  $E$ . It is a probability distribution function.

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

(2.7)

$E_F$  = Fermi energy or Fermi level

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

$T$  = absolute temperature in K

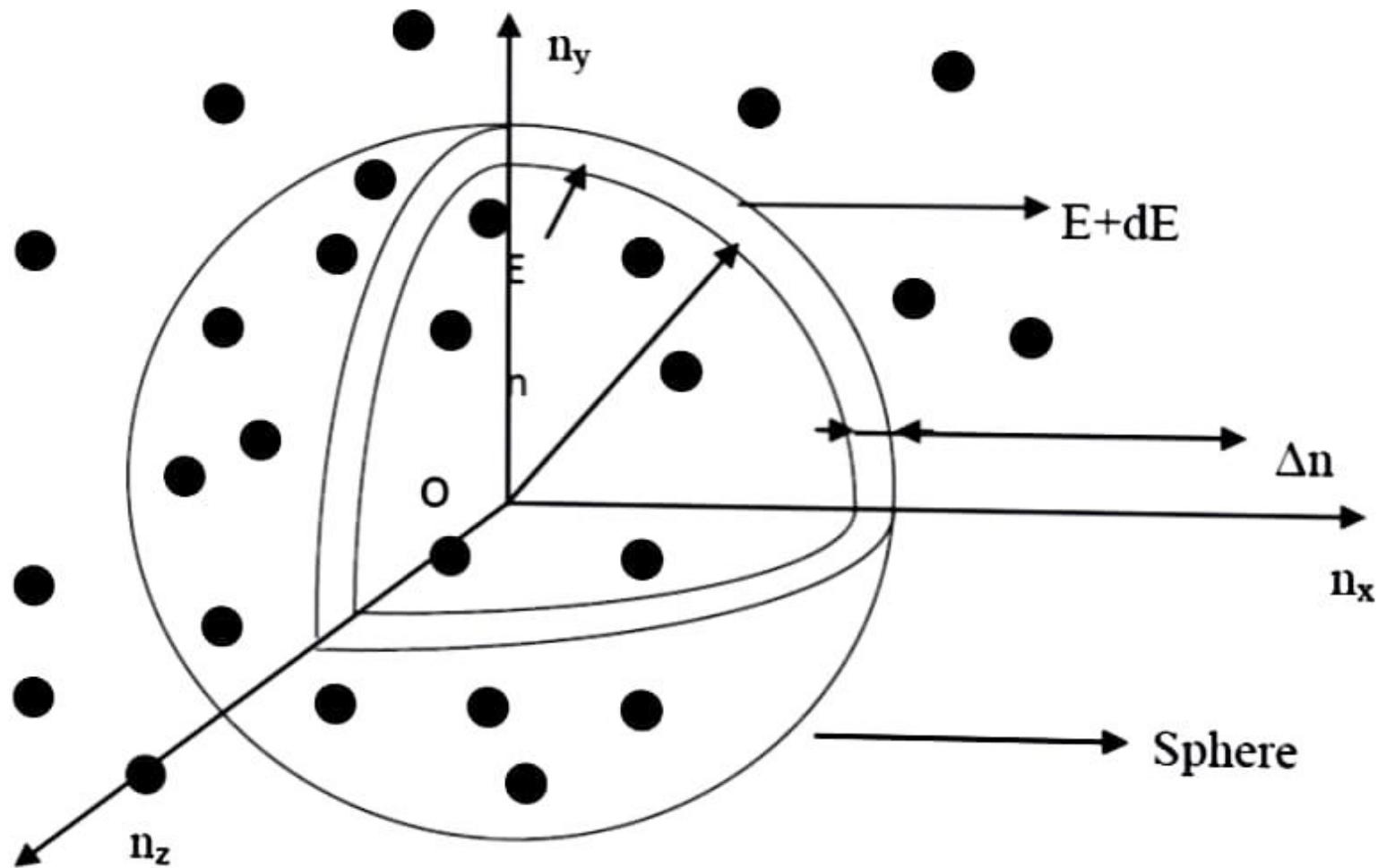


## DENSITY OF STATES IN METALS

- Fermi function – Probability of filling of electrons in an energy state.
  - It does not give information about the number of electrons that can be filled in an energy state.
- The number of available energy states are called as density of states.
- Density of states is defined as the number of available electrons per unit volume in an energy interval.



# DENSITY OF STATES IN METALS





## DENSITY OF STATES IN METALS

Density of states  $Z(E)dE$  is defined as the number of available electron states per unit volume in an energy interval  $dE$ .

$$\left. \begin{array}{l} \text{Number of Energy states} \\ \text{within the sphere} \end{array} \right\} n = \frac{4}{3} \pi n^3.$$

Since  $n_x, n_y, n_z$  takes Positive Values, we should consider only  $(1/8)^{\text{th}}$  of the sphere Volume



## DENSITY OF STATES IN METALS

∴ Number of available Energy states within the sphere,  $n = \frac{1}{8} \left[ \frac{4}{3} \pi n^3 \right]$  of radius  $n$  is, ————— ①

Similarly,

Number of available Energy states within the sphere of radii  $n+dn$  is,  $= \frac{1}{8} \left[ \frac{4}{3} \pi (n+dn)^3 \right]$  ————— ②

∴ Number of available Energy states b/w  $E$  &  $E+dn$  is,  $= \frac{1}{8} \left[ \frac{4}{3} \pi (n+dn)^3 - \frac{4}{3} \pi n^3 \right]$

Number of available Energy states b/w  $dE$  is,  $= \frac{1}{8} \left[ \frac{4}{3} \pi (n^3 + dn^3 + 3n^2 dn + 3n dn^2 - \cancel{\frac{4}{3} n^3}) \right]$



## DENSITY OF STATES IN METALS

Since the higher terms of  $dn$  is very small,  
 $dn^2$  &  $dn^3$  can be neglected.

$$\therefore Z(E) dE = \frac{1}{8} \cdot \frac{4}{3} \pi \cdot 3n^2 dn$$

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

We know,  
Energy of an electron,  $E = \frac{n^2 h^2}{8m l^2}$ .  $\text{--- (4)}$

$$n^2 = \frac{8ml^2 E}{h^2} \quad \text{--- (5)}$$

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



## DENSITY OF STATES IN METALS

Diff. eqn(5),

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

$$ndn = \frac{8ml^2}{2h^2} dE \quad \text{--- } ⑦$$

Eqn (3) Can be written as,

$$\chi(E) dE = \frac{\pi}{2} n(ndn) \quad \text{--- } ⑧$$



## DENSITY OF STATES IN METALS

Eqn (3) can be written as,

$$Z(E) dE = \frac{\pi}{2} n (ndn) \quad \text{--- (8)}$$

Subs eqn (6) & (7) in eqn (8),

$$Z(E) dE = \frac{\pi}{2} \cdot \left[ \frac{8ml^2 E}{h^2} \right]^{1/2} \cdot \left[ \frac{8ml^2}{2h^2} \right] dE.$$

$$= \frac{\pi}{2} \cdot \frac{1}{2} \left[ \frac{8ml^2}{h^2} \right]^{3/2} \cdot E^{1/2} dE.$$

$$Z(E) dE = \frac{\pi}{4} \left[ \frac{8ml^2}{h^2} \right]^{3/2} E^{1/2} dE.$$

$$Z(E) dE = \frac{\pi}{4} \left[ \frac{8m}{h^2} \right]^{3/2} l^3 E^{1/2} dE \quad \text{--- (9)}$$



## DENSITY OF STATES IN METALS

If  $l^3 = 1$ , then eqn (9) becomes,

$$Z(E)dE = \frac{\pi}{4} \left[ \frac{8m}{h^2} \right]^{3/2} \cdot E^{1/2} dE \quad \text{--- (10)}$$

Since each energy level provides two electrons

then,

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

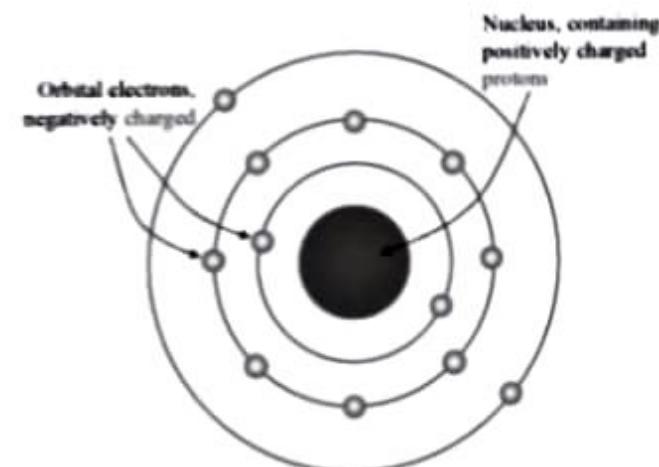
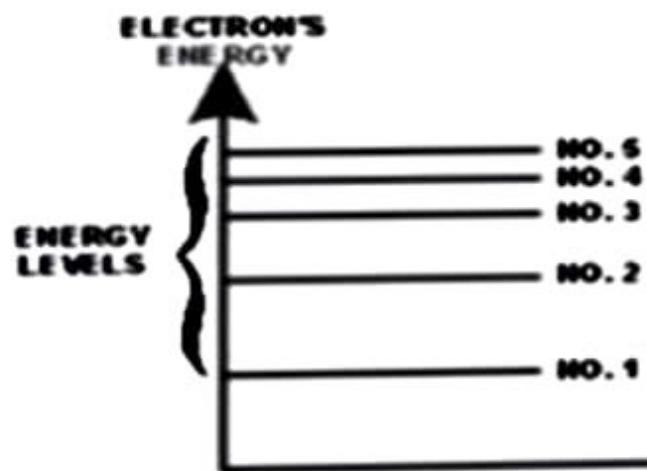
$$Z(E)dE = \frac{\pi}{2} \left[ \frac{8m}{h^2} \right]^{3/2} E^{1/2} dE \quad \text{--- (11)}$$

Eqn (11) represents the number of available energy states per unit volume.



## ENERGY BANDS IN SOLIDS

There are discrete energy levels in case of an isolated atom.



The following are the important energy band in solids:

- Valence band
- Conduction band
- Forbidden energy gap or Forbidden band



## ENERGY BANDS IN SOLIDS

### ❖ Valance band

The band of energy occupied by the valance electrons is called valence band. The electrons in the outermost orbit of an atom are known as valance electrons. This band may be completely or partial filled.

Electron can be move from one valance band to the conduction band by the application of external energy.



## ENERGY BANDS IN SOLIDS

### ❖ Conduction band

**The band of energy occupied by the conduction electrons is called conduction band. This is the uppermost band and all electrons in the conduction band are free electrons.**

**The conduction band is empty for insulator and partially filled for conductors.**



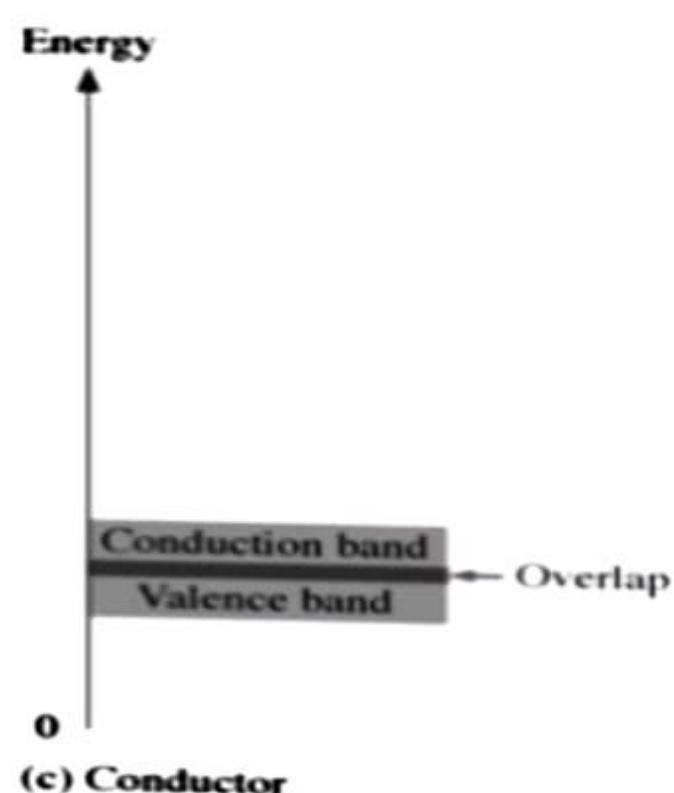
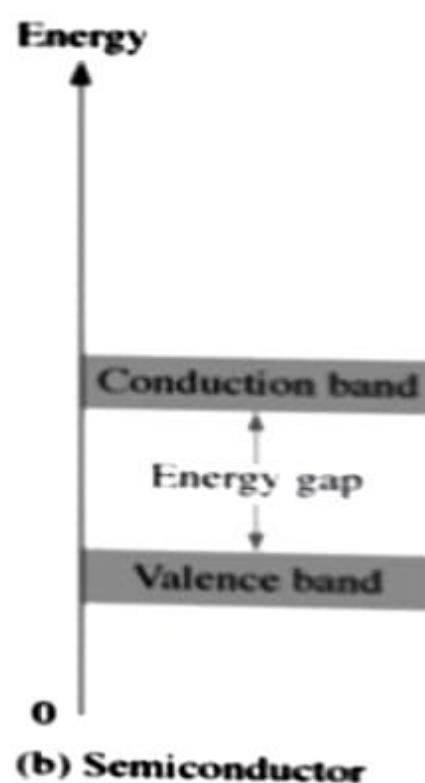
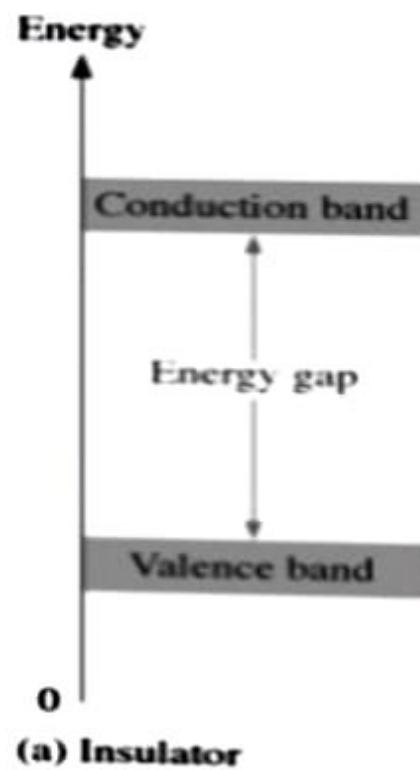
## ENERGY BANDS IN SOLIDS

### ❖ **Forbidden Energy Gap or Forbidden band**

The gap between the valance band and conduction band on energy level diagram known as forbidden band or energy gap.

Electron are never found in the gap. Electrons may jump from back and forth from the bottom of valance band to the top of the conduction band. But they never come to rest in the forbidden band.

# Energy Bands for, Insulator, Semiconductor and Conductor



**NON REPEATED EIGENVALUES**

**Example 1.2.1.** Find the Eigenvalues and Eigenvectors of the matrix

$$\begin{bmatrix} 1 & 1 \\ 3 & -1 \end{bmatrix}$$

Sol. Let  $A = \begin{bmatrix} 1 & 1 \\ 3 & -1 \end{bmatrix}$

**Step 1 :** To find the characteristic equation

The characteristic equation of  $A$  is  $|A - \lambda I| = 0$

i.e.,  $\lambda^2 - S_1\lambda + S_2 = 0$  where

$S_1$  = Sum of the main diagonal elements =  $(1) + (-1) = 0$

$S_2 = |A| = \begin{vmatrix} 1 & 1 \\ 3 & -1 \end{vmatrix} = -1 - 3 = -4$

∴ The characteristic equation is

$$\lambda^2 - (\lambda + (-4)) = 0$$

i.e.,  $\lambda^2 - 4 = 0$

**Step 2 :** To solve the characteristic equation

$$\lambda^2 = 4$$

$$\lambda = \pm 2$$

Hence the Eig

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AI Read aloud

Draw

Highlight

**Example 1.2.2. Find the Eigenvalues and Eigenvectors of**

$$\begin{vmatrix} 1 & 0 & -1 \\ 1 & 2 & 1 \\ 2 & 2 & 3 \end{vmatrix}$$

Sol. Let  $A = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 2 & 1 \\ 2 & 2 & 3 \end{bmatrix}$

**Step 1.** To find the characteristic equation.The characteristic equation of  $A$  is  $|A - \lambda I| = 0$ i.e.,  $\lambda^3 - S_1\lambda^2 + S_2\lambda - S_3 = 0$  where $S_1$  = Sum of the main diagonal elements =  $1 + 2 + 3 = 6$  $S_2$  = Sum of the minors of main diagonal elements

$$\begin{aligned} &= \begin{vmatrix} 2 & 1 \\ 2 & 3 \end{vmatrix} + \begin{vmatrix} 1 & -1 \\ 2 & 3 \end{vmatrix} + \begin{vmatrix} 1 & 0 \\ 1 & 2 \end{vmatrix} \\ &= (6 - 2) + (3 + 2) + (2 - 0) = 4 + 5 + 2 = 11 \end{aligned}$$

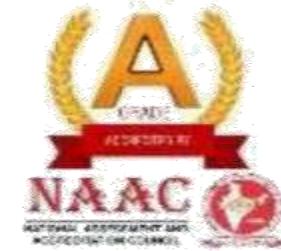
\*  $S_3 = |A| = \begin{vmatrix} 1 & 0 & -1 \\ 1 & 2 & 1 \\ 2 & 2 & 3 \end{vmatrix}$

$$= 1(6 - 2) - 0( ) + (-1)(2 - 4)$$

$$= 1$$



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## UNIT - IV

# SEMICONDUCTOR PHYSICS



**PRESENTED BY**  
**DR. C. RATHIKA THAYA KUMARI,**  
**Associate Professor,**  
**Department of Physics**

# Significance of Resistance – Ohm's Law

If the physical conditions like temperature, mechanical stress remains constant, the potential difference across two ends of a conductor is proportional to current flowing through a conductor.

$$V \propto I, \quad V = IR$$

The constant of proportionality R, is called Resistance of the conductor.

## Resistivity

At a constant temperature, the resistance R of a conductor is

- directly proportional to its length and
- inversely proportional to the area of cross section

$$R \propto L/A \quad \text{or} \quad R = \rho L/A$$

## Resistivity

Resistivity of the material is equal to the resistance offered by the wire of this material of unit length and unit cross sectional area.

The unit of resistance is **Ohm** and resistivity is **Ohm meter**.

## Two Probe Method – Measuring Resistivity of a material

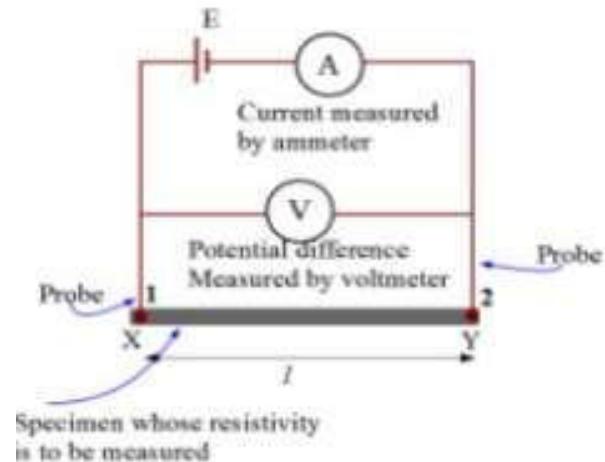
Consider a specimen XY in the form of a thin wire with uniform cross section as shown in the diagram. The resistivity for the specimen XY can be measured by two probe method. The battery E supplies the current in through probe 1 and current out through probe 2.

The current flowing in the specimen XY can be measured by the ammeter A. The potential difference between the two contacts probe 1 & 2 at the ends of the specimen XY is measured by the voltmeter V.

Let l be the length of the specimen between the probes and A is the area of cross section, then the resistivity of the specimen is,

$$\rho = \frac{RA}{L}$$

Where,  $R = V / I$



## Drawbacks of Two Probe method

- This method cannot be used for materials having random shapes.
- The chance of occurring errors due to contact resistance of measuring leads.
- Soldering the test leads will be difficult.
- In case of semiconductors, the heating of samples due to soldering results in injection of impurities into materials may affect the intrinsic electrical resistivity.

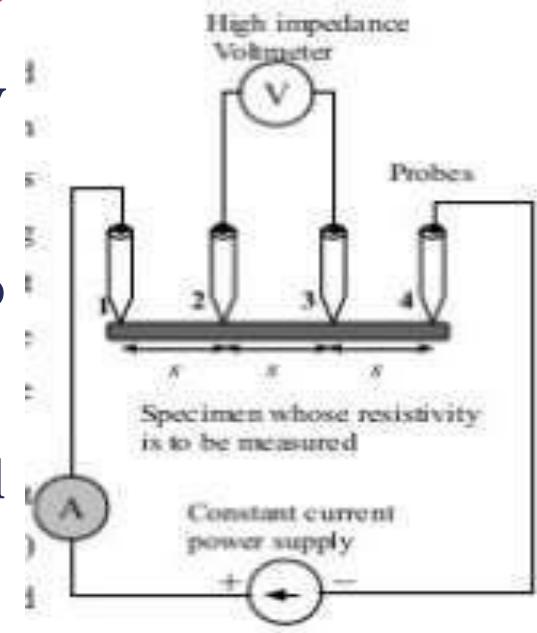
These drawbacks can be overcome by a **collinear equidistant four probe method**. This method provides the measurement of resistivity of specimen having wide variety of shapes but with uniform cross section.

# Four Probe Method – Linear Method

The 4-point probe set up consists of four equally spaced tungsten metal tips with finite radius.

Each tip is supported by springs on the end to minimize sample damage during probing.

The four metal tips are part of an auto mechanical stage which moves up and down during measuring.



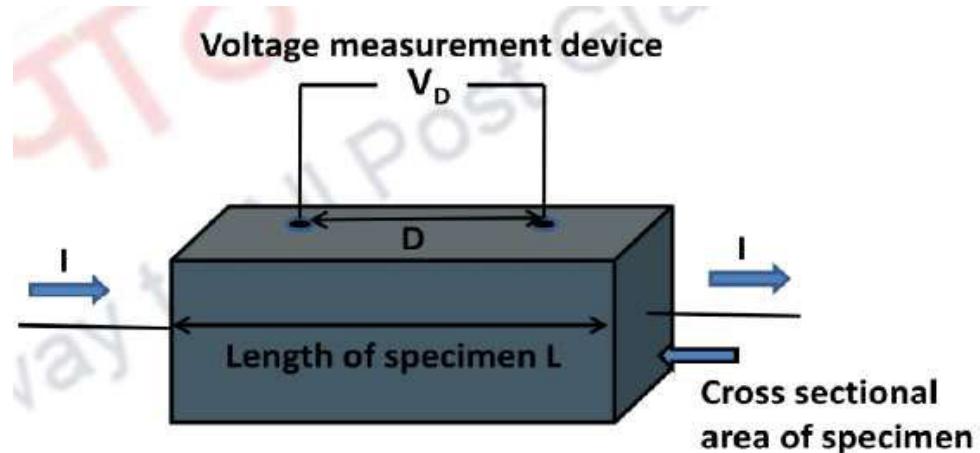
A high impedance current source is used to supply current through the outer two probes.

A voltmeter measures the voltage across the inner two probes to determine the sample resistivity.

The typical probe spacing should be approximately 1 mm.

# Four Probe Method – Vander Paw Method

This method is commonly used for measuring the resistivity of samples with low resistance value. The potential drop across



two probes is measured and the gap between them is taken as the sample length L. If the probes are not point contacts, true value of probe distance is gap between the centers and not the shortest distance between them.

$$\text{Resistivity, } \rho = \frac{V_D A}{D I}$$

A small voltage (of the order of few microvolts) might develop across the sample, thereby adding signal noise and increases the error. This error can be reduced by – shielding the cables, single point grounding, etc.

## Four Probe Method – Vander Paw Method

Four probe method equally applies to single crystal or bulk samples and can determine their resistances. Current flows through outer contacts near the sample edges and potential difference is gauged across inner contacts. Hence effect of interfacial resistance between electrodes and sample is eliminated. Thus, it is precise technique for low resistance measurements.

$$\text{Resistivity, } \rho = \frac{V_D A}{D I}$$

A small voltage (of the order of few microvolts) might develop across the sample, thereby adding signal noise and increases the error. This error can be reduced by – shielding the cables, single point grounding, etc.

# Four Probe Method – Vander Paw Method

The following conditions are required to satisfy for the resistivity measurement of a semiconductor.

1. The material possesses uniform resistivity in the measurement area.
2. If minority carriers are injected in semiconductor via the current-conducting electrodes, much of these carriers recombine at the electrodes and they have negligible influence on conductivity.
3. Surface to place the probes should be flat without any surface leakage.
4. The probes employed in measurement should touch the surface in straight line.
5. Diameter of contacts between the probes and semiconductor should be smaller than the gap between the probes.

# Four Probe Method – Vander Paw Method

## **Applications:**

1. Remote sensing areas.
2. Resistance thermometer.
3. Induction hardening processes.
4. Precise estimation of geometrical factors.
5. Characterization of fuel cells bipolar plates.

# HALL EFFECT

- The measurement of conductivity will not determine, whether the conduction is due to holes or electrons.
- Therefore, Hall effect is used to distinguish between two types of charge carriers and their carrier densities.
- Also, it is used to determine the mobility of charge carriers.

## What is Hall effect?

When a current carrying conductor is placed in a magnetic field. An electric field is placed inside the material in a direction normal to both the current and the magnetic field. This phenomenon is known as **Hall effect** and the generated voltage is called **Hall voltage**.

# HALL EFFECT IN n-type SEMICONDUCTOR

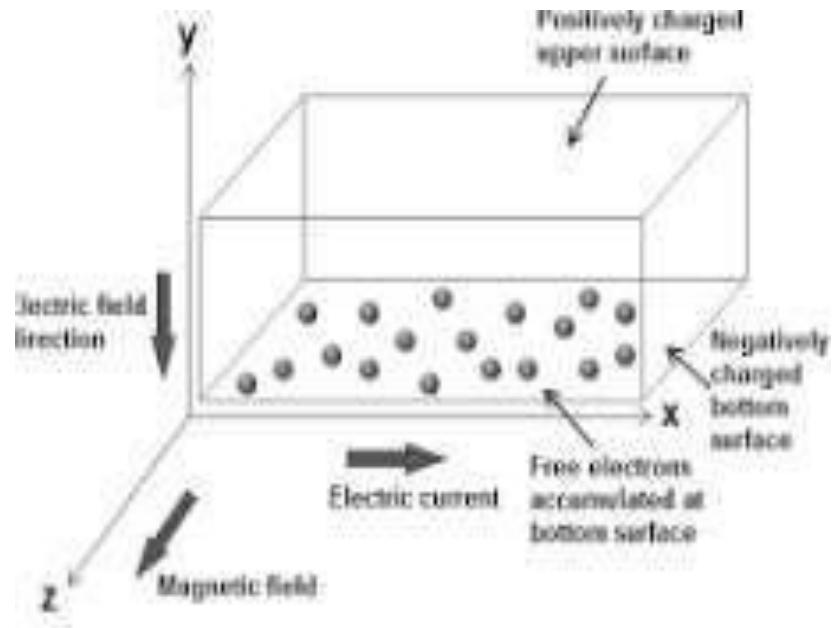
In an n type semiconductor, the current is allowed to pass along the x-direction and the magnetic field along z-direction.

As a result, Hall voltage is developed along the y-direction.

Since the direction of current is along left to right, the electrons moves from right to left in the x-direction.

Due to the applied magnetic field, electrons move towards downward direction with velocity  $v$ . A potential difference is developed and gives a field  $E_H$  in the negative direction.

$$\text{The Hall Coefficient } R_H = -(1/ne)$$



# HALL EFFECT IN p-type SEMICONDUCTOR

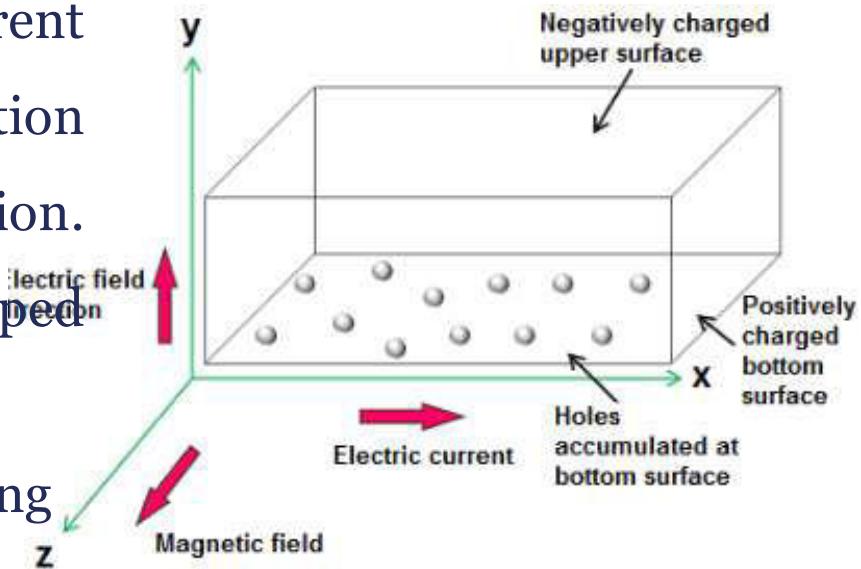
In a p type semiconductor, the current is allowed to pass along the x-direction and the magnetic field along z-direction.

As a result, Hall voltage is developed along the y-direction.

Since the direction of current is along left to right, the holes also moves along the same direction.

Due to the applied magnetic field, holes move towards downward direction with velocity  $v$ . A potential difference is developed and gives a field  $E_H$  in the positive direction.

$$\text{The Hall Coefficient } R_H = (1/ne)$$



# MOBILITY of Charge Carriers

In general, the Hall coefficient can be written as,  $R_H = -(1/ne)$

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

But for Semiconductors, velocity is taken as average velocity, so  $R_H$  of an n type semiconductor is modified as,

$$R_H = -\frac{3\pi}{8} \left( \frac{1}{n_e e} \right)$$

$$R_H = \frac{-1.18}{n_e e}$$

We know the conductivity for n type is  $\sigma_e = n_e e \mu_e$

$$(or) \mu_e = \frac{\sigma_e}{n_e e}$$

# MOBILITY of Charge Carriers

From equation (1) we can write

$$\frac{1}{n_e e} = \frac{R_H}{1.18}$$

Substituting equation (3) in equation (2) we get

$$\mu_e = -\frac{\sigma_e R_H}{1.18}$$

∴ The mobility of electron is in an n-type semiconductor is

$$\mu_e = \frac{-\sigma_e V_H b}{1.18 I_s B}$$

$$\left[ \therefore R_H = \frac{V_H b}{I_s B} \right]$$

## DEEP LEVEL TRANSIENT SPECTROSCOPY- DLTS

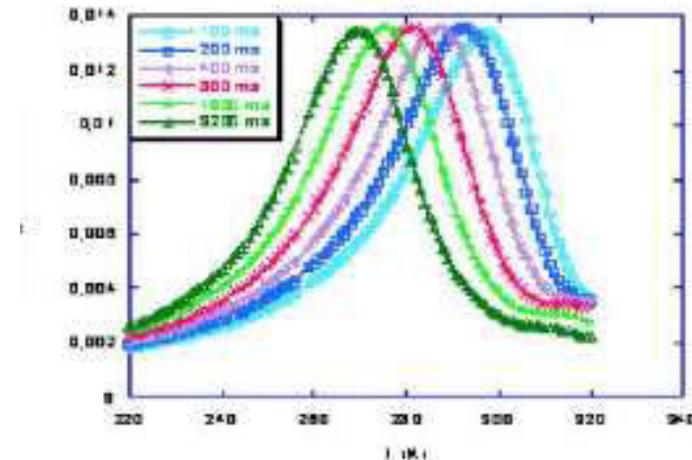
- is an experimental tool for studying electrically active defects (a.k.a. charged carrier traps) in semiconductors.
- enables to establish fundamental defect parameters (some considered as defect “finger prints”) and measure their concentration in the material.
- has a higher sensitivity than almost any other semiconductor diagnostic technique.
- features simple technical design.

# DEEP LEVEL TRANSIENT SPECTROSCOPY- DLTS

## Working Principle

- semiconductor junction (p-n diode or Schottky diode) is a subject to the voltage pulse at different temperatures
- capacitance transients are monitored and spectrum is generated which exhibits peaks for each deep levels
- the height of the peak is proportional to the trap density; sign distinguishes minority from majority traps; position of the peak determine the fundamental parameters governing thermal emission and capture (activation energy and cross section)

The application of the method has led to the discovery of new phenomena and has provided a unique tool for the understanding of materials processing for semiconductor devices.



## Fundamental laws of Absorption - Lambert's law

When a monochromatic radiation is passed through a solution, the decrease in the intensity of radiation ( $-dI$ )

with thickness of the medium ( $dx$ ) is directly proportional to the intensity of incident light ( $I$ )

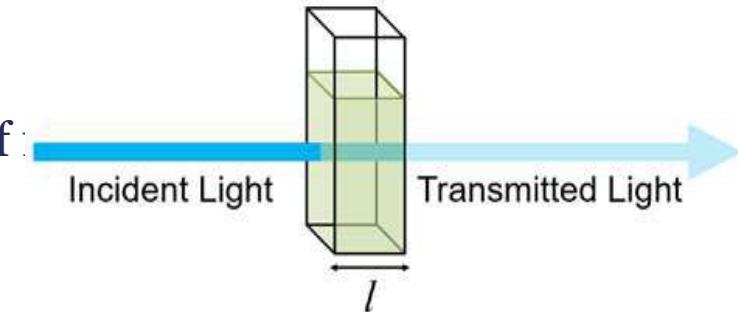
Let  $I$  be the intensity of  
 $dx$  be the thickness of the medium

Then

$$-\frac{dI}{dx} \propto I$$

$$-\frac{dI}{dx} = KI$$

Integrate equation between limit  $I = I_0$  at  $x = 0$  and  $I = I$  at  $x = l$



$$-\int_{I_0}^I \frac{dI}{I} = K \int_0^l dx$$

## Fundamental laws of Absorption - Lambert's law

$$2.303 \log \frac{I}{I_0} = Kl$$

$$\log \frac{I}{I_0} = \frac{K}{2.303} l$$

$$\log \frac{I}{I_0} = A \quad A \text{ is the Absorbance}$$

$$\frac{K}{2.303} = \epsilon \quad \epsilon \text{ is the Absorption coefficient}$$

$$A = \epsilon \cdot l \quad \text{is the Lambert's law}$$

The absorbance is directly proportional to the length of the light path (l), which is equal to the width of the cuvette.

## Fundamental laws of Absorption – Beer's law

When a monochromatic radiation is passed through a solution, the decrease in the intensity of radiation ( $-dI$ ) with thickness of the medium ( $dx$ ) is directly proportional to the intensity of the incident light ( $I$ ) as well as concentration of the solution ( $C$ ).

Let  $I$  be the intensity of incident radiation

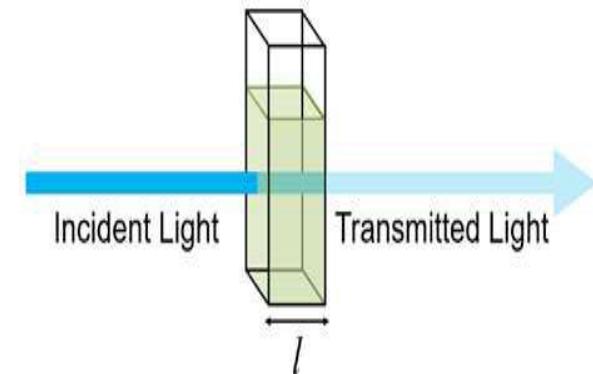
$dx$  be the thickness of the medium, then

$$-\frac{dI}{dx} \propto CI$$

$$-\frac{dI}{dx} = KCI$$

Integrate equation between limit  $I$

$= I_0$  at  $x = 0$  and  $I = I$  at  $x = l$



$$-\int_{I_0}^I \frac{dI}{I} = KC \int_0^l dx$$

## Fundamental laws of Absorption – Beer's law

$$2.303 \log \frac{I}{I_0} = KCl$$

$$\log \frac{I}{I_0} = \frac{K}{2.303} cl$$

$$\log \frac{I}{I_0} = A \quad A \text{ is the Absorbance}$$

$$\frac{K}{2.303} = \epsilon \quad \epsilon \text{ is the Molar extinction coefficient}$$

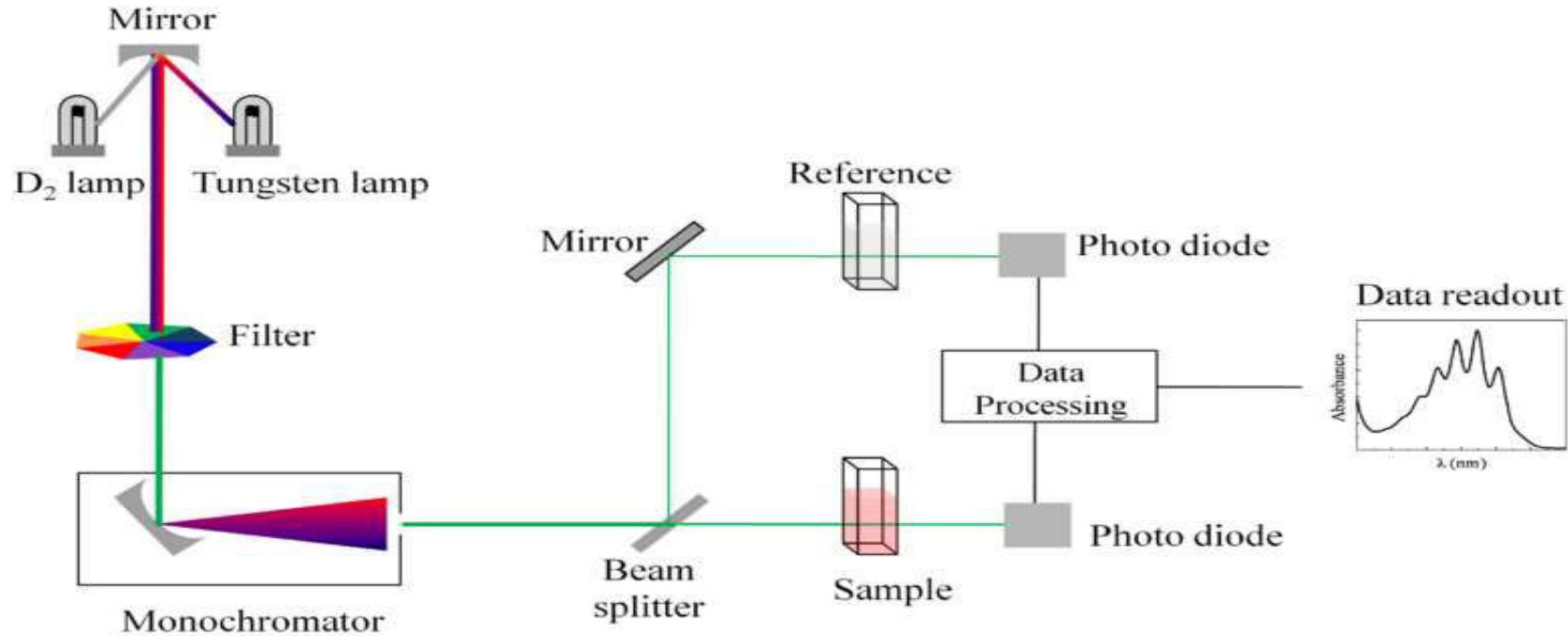
$A = \epsilon \cdot c \cdot l$       This is the Beer's law.

- The absorbance is directly proportional to the concentration (c) of the solution of the sample used in the experiment
- The absorbance is directly proportional to the length of the light path (l), which is equal to the width of the cuvette.

# Instrumentation of UV-visible Spectroscopy

- Spectroscopy is the measurement and interpretation of electromagnetic radiation absorbed or emitted when the molecules or atoms or ions of a sample moves from one energy state to another energy state.
  
- UV-visible spectroscopy is type of absorption spectroscopy in which light of UV-visible region 100 to 700 ( UV region 100-400 nm and Visible region 400-700nm) is absorbed by the molecule which results in the excitation of the electrons from the ground state to higher energy state.

# Instrumentation of UV-visible Spectroscopy



# Instrumentation of UV-visible Spectroscopy

## Hydrogen lamp or Deuterium Lamp

- In hydrogen discharge lamp pair of electrodes is enclosed in a glass tube (provided with silica or quartz window for UV radiation to pass through) filled with hydrogen gas
- When current is passed through these electrodes maintained at high voltage, the discharge of electron occurs which excites hydrogen molecules which in turn causes emission of UV radiations in near UV region

## Tungsten halogen lamp

- The bulbs contain a filament of tungsten fixed in evacuated condition and then filled with inert gas .The filament can be heated up to 3000K. Tungsten reacts with iodine to form Tungsten-Iodine complex which migrates back to the hot filament where it decomposes and tungsten get deposited.

# Instrumentation of UV-visible Spectroscopy

## Mirror

These are used to reflect, focus or collimate light beams in spectrophotometer . To minimize the light loss, mirrors are aluminized on their front surface.

## Monochromators

It is device used to isolate the radiation of the desired wavelength from wavelength of continues spectra. Following types of monochromatic devices used are Filters, Prisms, Gratings.

## Filters

It works by selective absorption of unwanted radiation and transmits the radiation (narrow band of radiation) which is required  
e.g. Glass and gelatin filters

# Instrumentation of UV-visible Spectroscopy

## Prisms

- It is made of quartz or fused silica. When light is passed through glass prism, dispersion of polychromatic light in rainbow occurs. Now by rotation of the prism different wavelength of spectrum can be made to pass through in exit slit on the sample.

## Sample holder/Cuvettes

- The cells or cuvettes are used for handing liquid samples. It may either be rectangular or cylindrical in nature. It is made of quartz or fused silica .

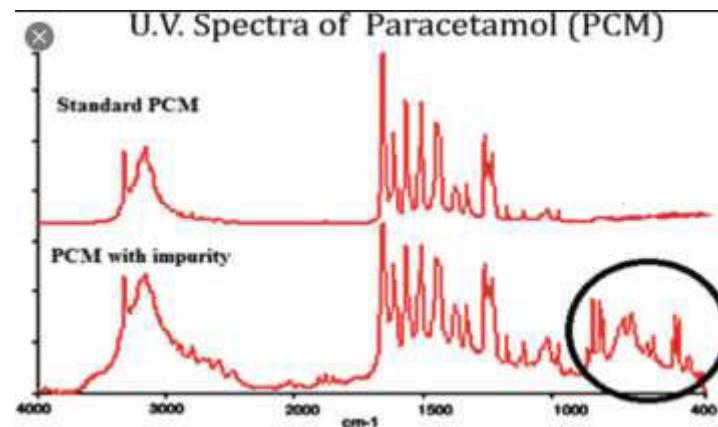
## Detectors

- Device which converts light energy in to electrical signals, that are displayed on readout devices. The transmitted radiation falls on the detector which determines the intensity of radiation absorbed by sample.

# Instrumentation of UV-visible Spectroscopy

## Working:

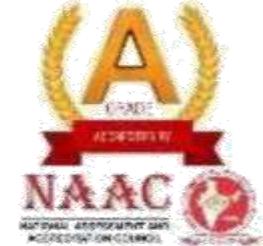
The radiation from the source is passed through the monochromator where it splitted into two equal beams, one half is passed into the sample cell and another half is passed into the reference cell containing solvent. The detector will measure the comparison of intensities of beam of light. If the sample absorbs light then the intensity of sample beam is less than the intensity of reference beam. It will be recorded as a signal in recorder. The instrument gives output graph.



**THANK YOU**



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## UNIT - V

# SEMICONDUCTOR PHYSICS



**PRESENTED BY**

**DR. C. RATHIKA THAYA KUMARI,**  
**Associate Professor,**  
**Department of Physics**



## NANO MATERIALS

In recent years, nanotechnology is one of the most important and developing fields in science, engineering and technology and bio medical.

Nano means “billionth”  $10^{-9}$  m.

Atoms are very small and the diameter of a single atom can vary from 0.1 to 0.5 nm. Nanotechnology deals with various structures and matter having dimensions of the order of a billionth of meter.

## NANO TECHNOLOGY

Nano-technology is the design, fabrication, characterization and applications of materials at nano level and converting them into useful devices.

## NANO SCIENCE

Nano science is the study of phenomena and manipulation of materials between molecular and nanometer size.



# NANO MATERIALS - INTRODUCTION

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Term “nano” has been derived from Greek word “nanos” which means **dwarf**.

## **Nanotechnology:**

It deals with the small structures or small sized materials. The dimension spans from sub nanometer to several 100 nanometers

**Nanometer: (nm) – One billionth of a meter or  $10^{-9}$  m.**

One nm = 10 hydrogen atoms or five silicon atoms.

## **Bulk materials:**

Materials in the micro scale exhibit physical properties same as that of the bulk form.



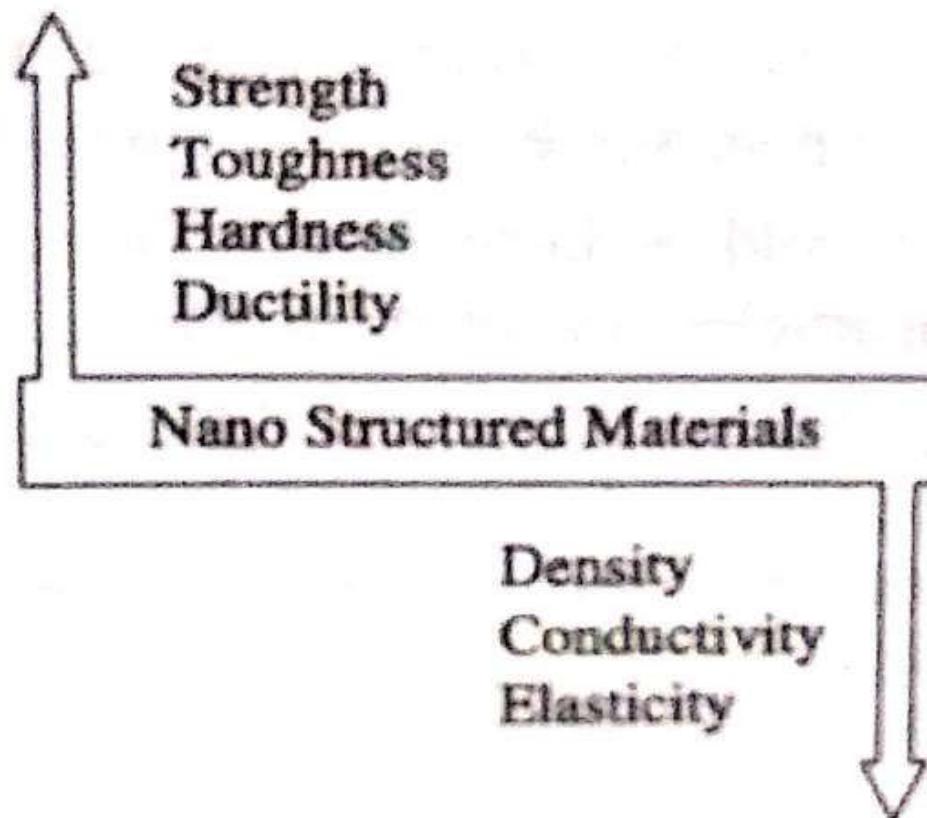
## DIFFERENCE BETWEEN NANO AND BULK MATERIALS

- The size of nanoparticles are less than 100 nm in diameter but bulk particles are larger in microns.
- Molecule is a collection of atoms, nanoparticles are collection of few molecules less than 100 nm but bulk particles contains thousands of molecules.
- Hardness of nanomaterials are five times more than the bulk materials.
- Strength is 3-10 times higher than the bulk materials.
- Nanoparticles possesses size dependant properties but bulk materials possess constant physical properties.
- Nanoparticles due to its size, possess unexpected optical properties.i.e Absorption of solar radiation in photovoltaic cell containing nanoparticles are higher than the film (bulk).



## PROPERTIES OF NANO MATERIALS

All the properties of nanomaterials depend on their size. The properties like hardness, strength, ductility, melting point and densities vary for nanomaterials.





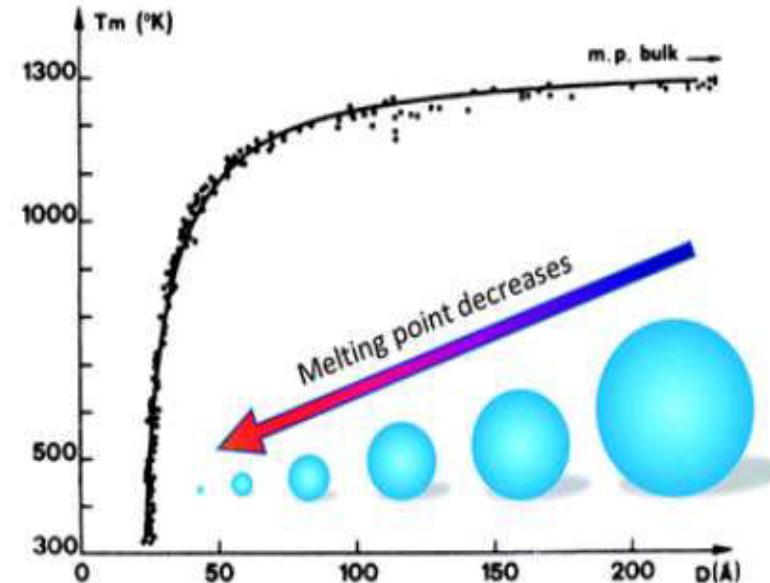
# PROPERTIES OF NANO MATERIALS

## Nanomaterials:

Materials in the nanoscale which exhibit physical properties different from the bulk form.

## Physical Properties:

- The melting point of the nanomaterials possess low melting point It is mainly due to presence of huge fraction of surface atoms in the total amount of atoms.
- Below 50 nm the melting point of gold drops down immediately .
- The surface energy is high.





# PROPERTIES OF NANO MATERIALS

## Mechanical Properties:

- The mechanical strength of the nanomaterials is enhanced compared to the bulk material and this is mainly due to the highly internal perfection (arrangement of atoms) of the nanomaterials
- For eg: Nano material copper has 5 times micro hardness greater than bulk material
- The bulk materials have high probability of imperfections such as dislocation and defects which are mainly eliminated in the smaller structures (nano).

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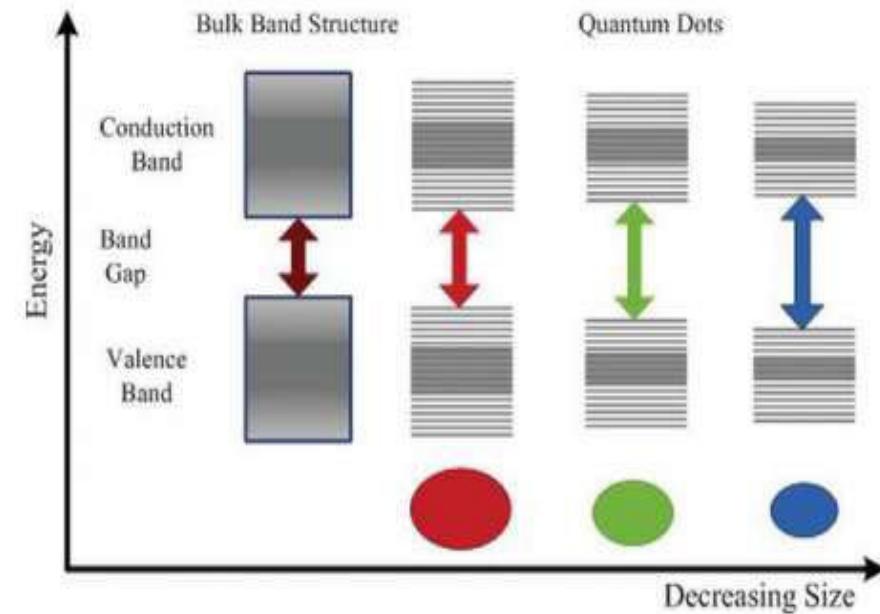
# UNIT

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## PROPERTIES OF NANO MATERIALS

### Optical Properties:

- When the size of the particle is reduced to nanoparticle, then there is a shift in absorption spectra to blue region.
- As semiconductor particle size is reduced, the bandgap is increased .
- Nano crystals with large band gap (Eg energy gap) emit lower wavelength colors such as blue and green, whereas the nano crystals with small band gap emit longer wavelength such as red.





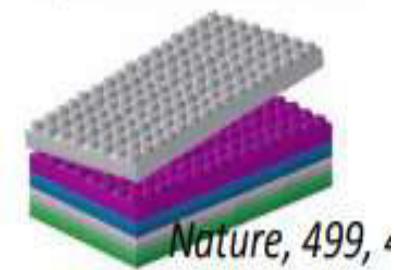
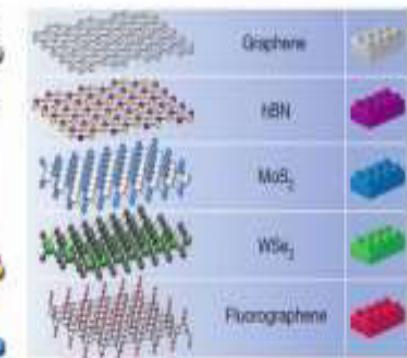
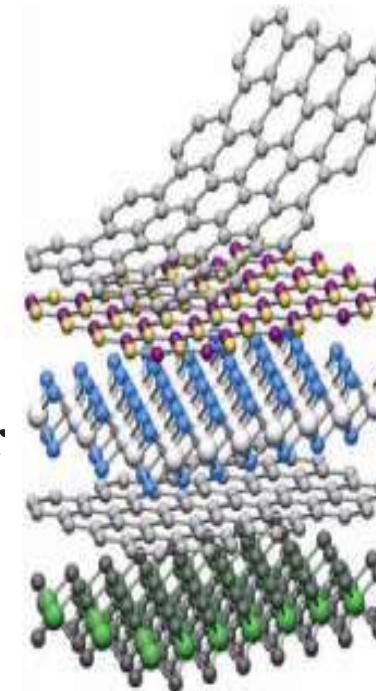
# NANO MATERIALS – Low Dimensional Materials

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In 2 Dimensions, Single atom thickness films

- Flexible electronics
- Sensors



In 1 Dimensions, Nano wires,

- Quantum electronics
- Bio Sensors
- Solar cell, Photo detector

In 0 Dimensions, Quantum dots

- Single electron transistor



# CLASSIFICATION OF NANO MATERIALS

## 0D nanoparticles:

All the three dimensions of the material is in the nano scale.

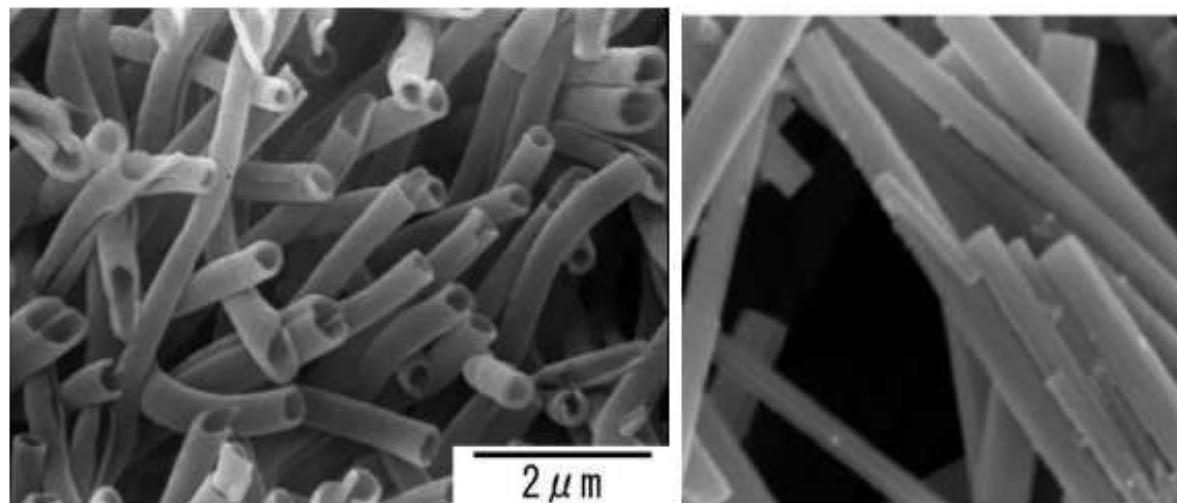
i.e., dimension is less than 100 nm. eg: Quantum dots.

## 1D nanoparticles:

One dimension of the material is out of the nano scale and the other two dimensions are restricted to nano scale.

eg: Nanotubes, nanorods and nanowires.

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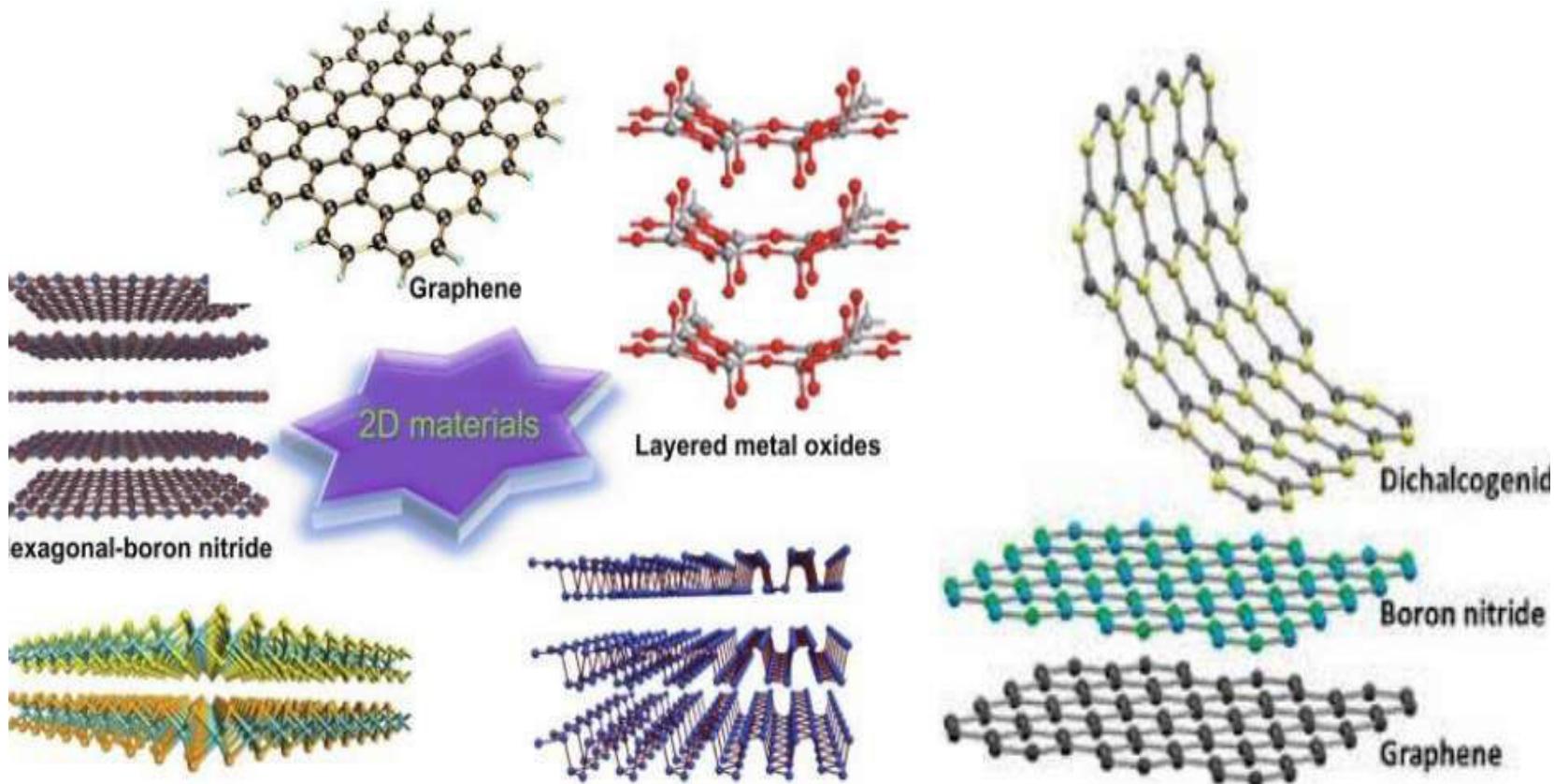


# CLASSIFICATION OF NANO MATERIALS

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**2D nanoparticles:** Two dimensions of the material is out of the nano scale and the third dimension is restricted to nano scale and the thickness is equal to one atomic layer. eg: Nanosheets, Nanolayers.





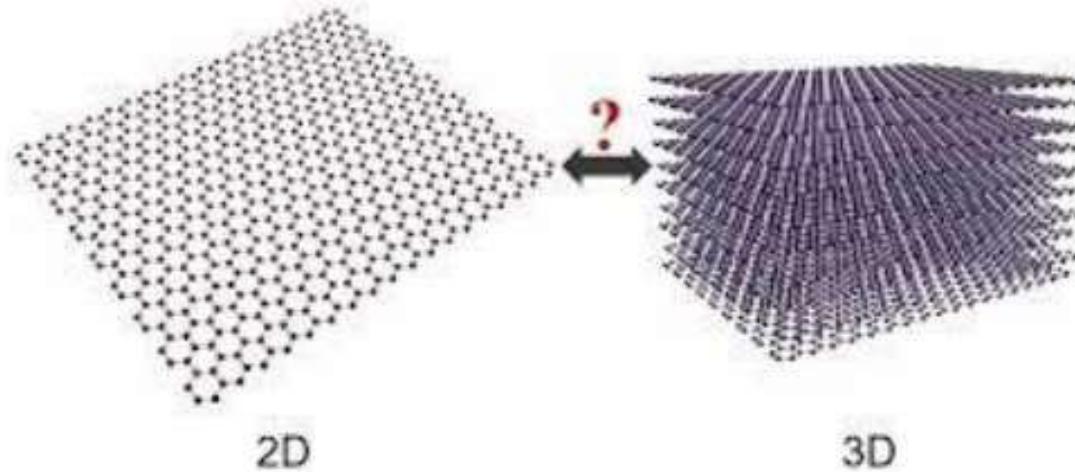
# CLASSIFICATION OF NANO MATERIALS

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## 3D nanoparticles:

Bulk three dimensions of the material is out of nano scale is known to be bulk material. Polycrystalline in nature All the three dimensions XYZ are greater than 100nm. Multilayered





# CLASSIFICATION OF NANO MATERIALS

## Quantum Well

- It is a two dimensional system
- The electron can move in two directions and restricted in one direction.

## Quantum Wire

It is a one dimensional system

The electron can move in one direction and restricted in two directions.

## Quantum Dot

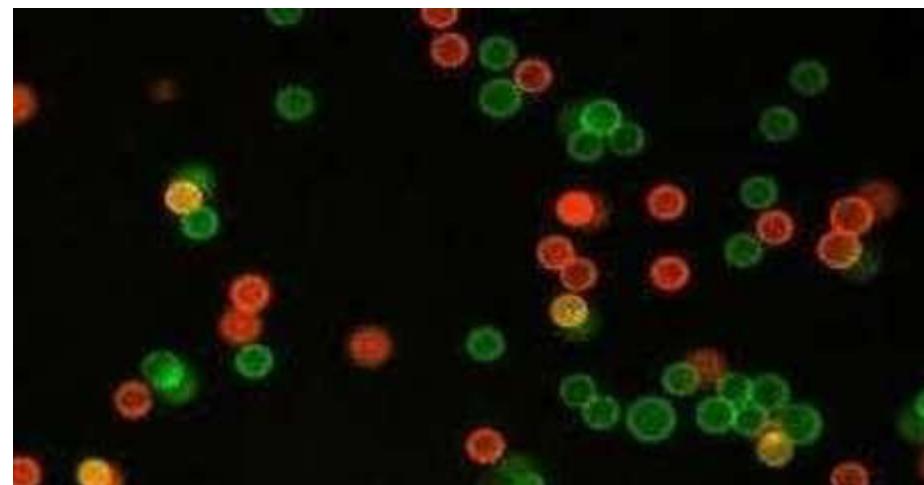
It is a zero dimensional system

The electron movement was restricted in entire three dimensions.



## QUANTUM DOTS

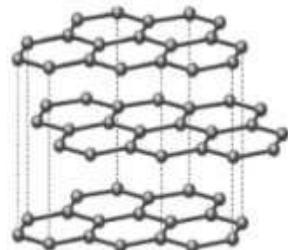
- Are nanoparticles / structures that exhibit 3 D quantum confinement, which leads to many unique optical and transport properties. These are generally regarded as semiconductors.
- The energy levels depend on the size and also on shape of the quantum dot. Smaller dot higher band gap energy, energy levels increase in energy and spread out more. Eg- CdSe,PbSe





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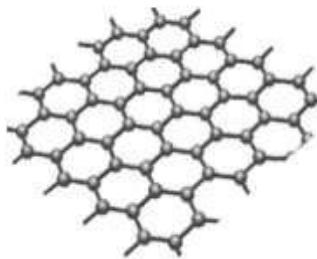
## CARBON BASED NANO MATERIALS



Graphite (3D)

van der Waals stack of graphene  
Conductor

Stack

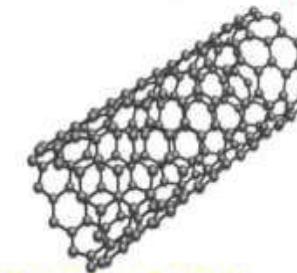


Graphene (2D)

Single-atom-thick carbon layer  
sp<sup>2</sup> bonding of carbons  
Semi-metal

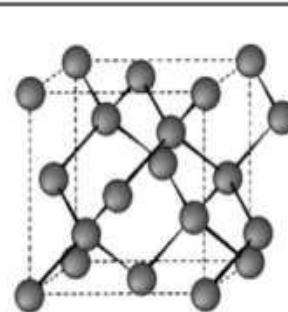


Roll



Carbon nanotube (1D)

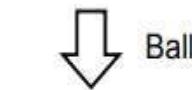
Rolled graphene  
Semiconductor (2/3) or metal (1/3)



Diamond (3D)

sp<sup>3</sup> bonding of carbons  
Wide band gap (5.5 eV)

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Fullerene (0D)

Wide band gap (5.5 eV)

Single element carbon shows  
different functionality  
depending on its dimension



# PROPERTIES OF GRAPHENE

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	Graphene	Si
Electrical conductivity	~100,000 cm <sup>2</sup> /Vs	450 cm <sup>2</sup> /Vs
Thermal conductivity	~5000W/K.m	1.3 W/K.m
Young's modulus	1 TPa	130~170 GPa
Transparency	O	X
Flexibility	O	X



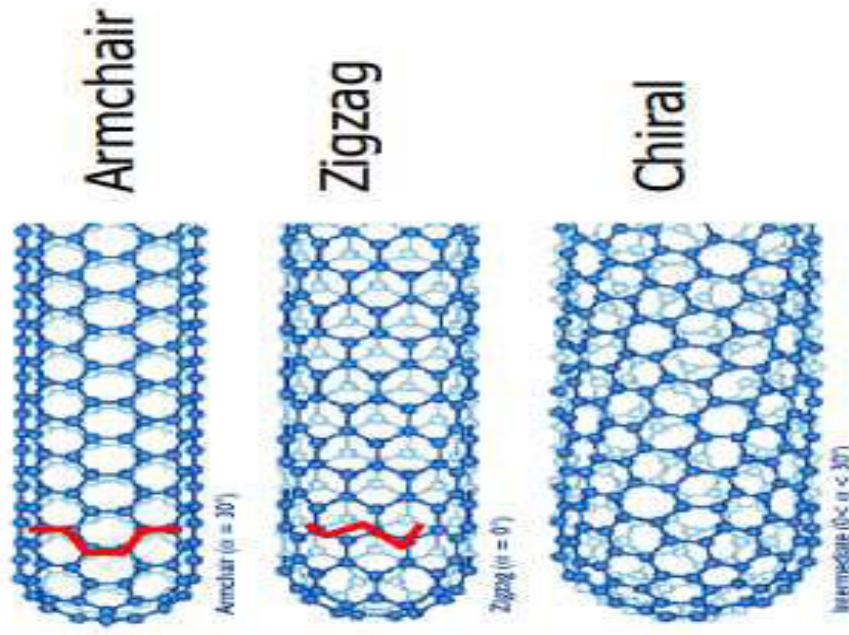
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## PROPERTIES OF GRAPHENE

**Diameter determines band gap**

**Chirality determines semiconductor or metal**



Metallic

Semiconducting

Intermediate



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## PROPERTIES OF CNTs

	CNT	Graphene	Si
Electrical conductivity	~100,000 cm <sup>2</sup> /VS	>100,000 cm <sup>2</sup> /VS	450 cm <sup>2</sup> /Vs
Thermal conductivity	~5000W/K.m	~5000W/K.m	1.3 W/K.m
Young's modulus	0.9 ~1.1TPa	1 TPa	130~170 GPa
Transparency	O	O	X
Flexibility	O	O	X
Band gap	Semiconductor & Metal	Semi-metal	Semiconductor



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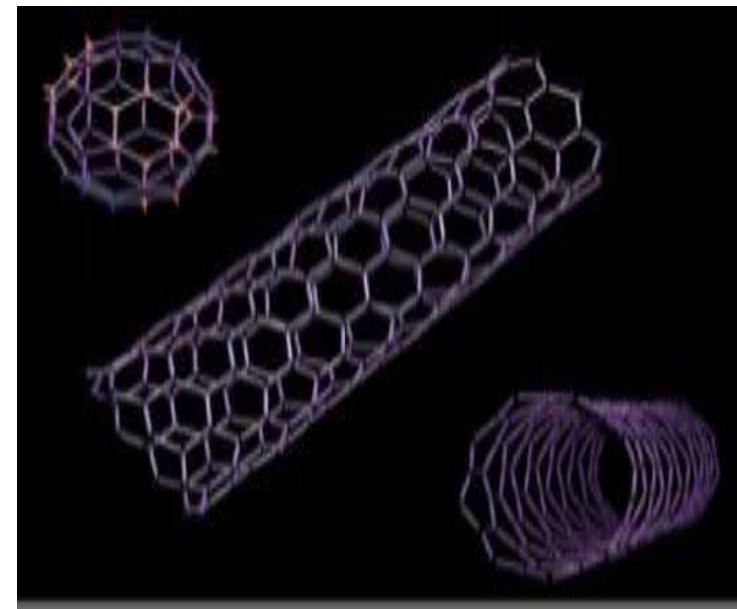
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## CARBON NANO TUBE – (CNT)

- A carbon nanotube is a tube shaped material made of carbon, having a diameter measuring on the nanometre scale.
- CNTs are formed from the graphite sheet and the graphite layer appears like a rolled up continuous unbroken hexagon mesh and carbon molecules at the apexes of the hexagon.

Nanotubes are the members of the fullerenes and structural family.

Their name is derived from the long, hollow structure with the walls formed by one atom thick sheets of carbon called graphene





## TYPES OF CARBON NANO TUBE – (CNT)

CNTs are classified mainly in to two types:

- Single walled Nanotubes
- Multiwalled Nanotubes

Some other related structures of CNT are:

- Torus
- Nanobud
- Graphenated CNTs – g-CNT
- Nitrogen doped CNTs – N-CNT
- Peapod
- Cup stacked Carbon nanotubes

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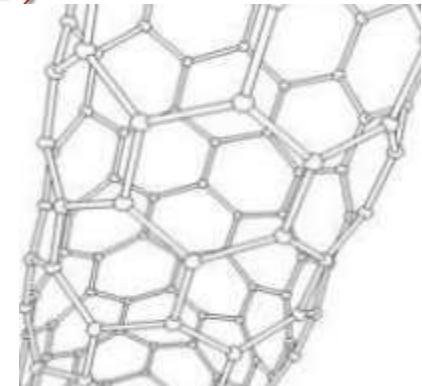


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## SINGLE WALLED NANO TUBE – (CNT)

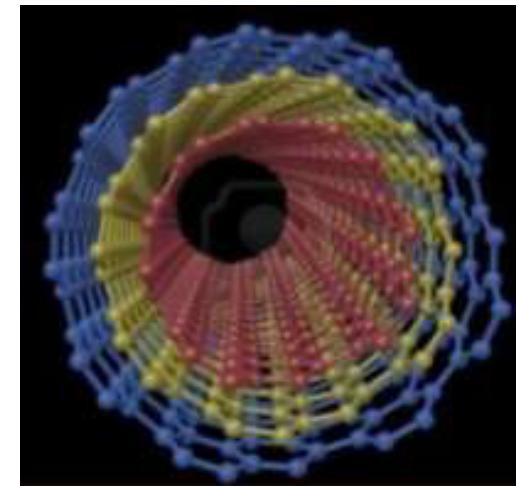
A one atom thick layer of graphene into seamless cylinder. Their electrical conductivity can show metallic or semiconducting behavior. Its diameter is 1 nm and the band gap is 0-2 eV.



## MULTI WALLED NANO TUBE – (CNT)

It consists of multiple rolled layers like concentric tube of graphene. Its inter layer distance is 3.4 Å.

There are two models to describe the structure of Multiwalled CNT.



- Russian doll model
- Parchment doll model

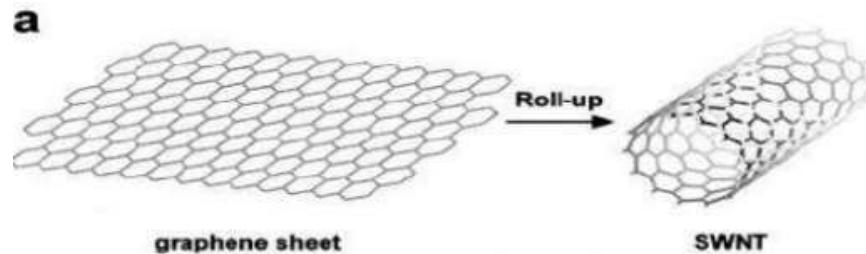


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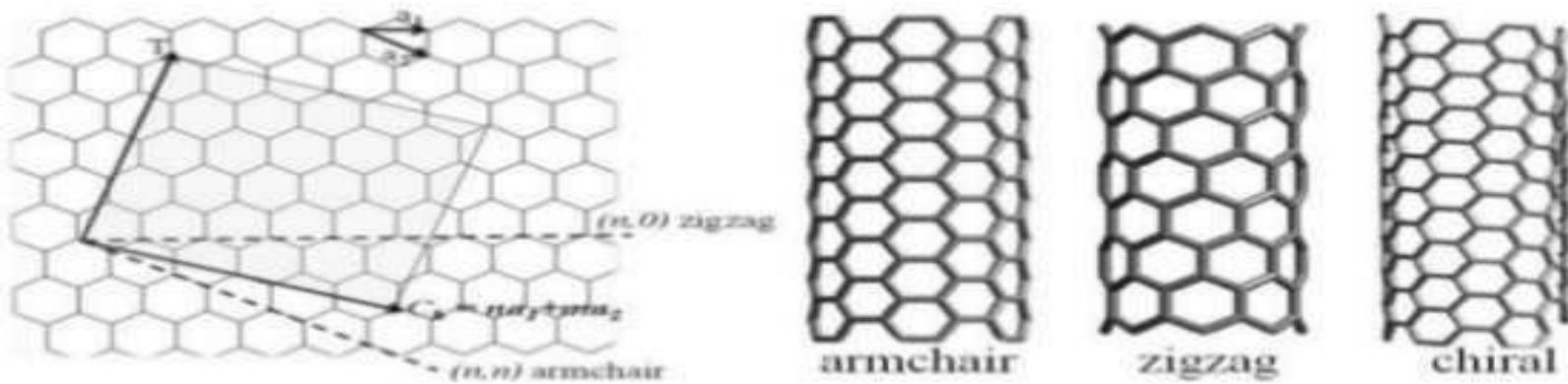
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## STRUCTURES OF CNTS

Rolling up a graphene sheet to form a tube



- *The way the graphene sheet is wrapped is represented by a pair of indices  $(n,m)$  called the chiral vector.*
- *The integers  $n$  and  $m$  denote the number of unit vectors along two directions in the honeycomb crystal lattice of graphene*
- *If  $m = 0$ , the nanotubes are called "zigzag". If  $n = m$ , the nanotubes are called "armchair". Otherwise, they are called "chiral".*





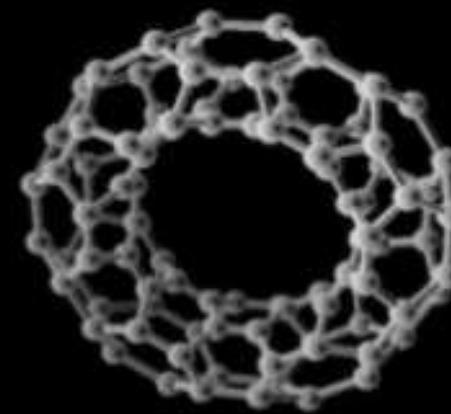
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## RELATED STRUCTURES OF CNTS

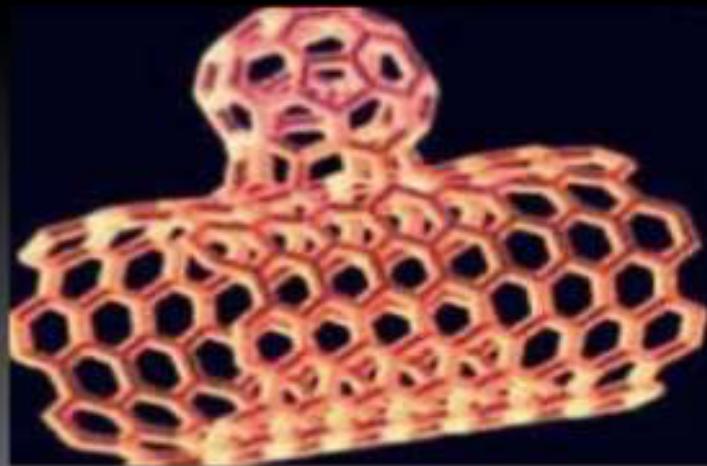
### TORUS :-

It is a carbon nanotube bent in a torus shape (i.e. doughnut shape)



### NANOBUD :-

Carbon Nanobud are created combining carbon nanotubes and fullerenes.





## RELATED STRUCTURES OF CNTS

### GRAPHENATED CARBON NANOTUBE

They are now hybrids that combines graphitic foliates grown along the side walls of multi walled CNTs.

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### NITROGEN DOPED CARBON NANOTUBES

They are used for enhancing storage capacity of Li-ion batteries. N-doping provides defects in the walls of CNTs allowing for LI ions to diffuse into inner wall space.



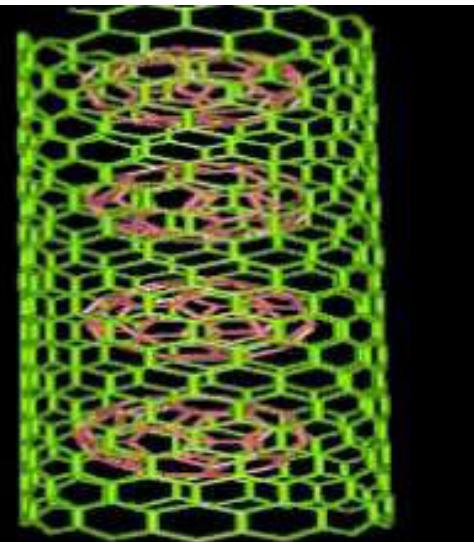
# RELATED STRUCTURES OF CNTS

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## *Peapod :-*

A carbon peapod is a novel hybrid carbon material which traps fullerene inside a Carbon nanotube.



## *CUP-STACKED CARBON NANOTUBES :-*

CSCNTs exhibit semiconducting behaviours due to the stacking microstructure of graphene layers.





# PROPERTIES OF CNTS

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## Strength :-

Carbon nanotubes are the strongest, flexible and stiffest materials yet discovered in terms of tensile strength and elastic modulus respectively.

## Hardness :-

The hardness (152 Gpa) and bulk modulus (462–546 Gpa) of carbon nanotubes are greater than diamond, which is considered the hardest material.

## Electrical Properties:-

Because of the symmetry and unique electronic structure of graphene, nanotube has a very high current carrying capacity.



## PROPERTIES OF CNTS

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### Thermal Conductivity:-

All nanotubes are expected to be very good thermal conductors along the tube.

### EM Wave absorption:-

There has been some research on filling MWNTs with metals, such as Fe, Ni, Co, etc., to increase the absorption effectiveness of MWNTs in the microwave regime.

### Thermal properties:-

All nanotubes are expected to be very good thermal conductors along the tube, but good insulators laterally to the tube axis.



# SYNTHESIS OF CNTS

There are three methods to produce CNTs.

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- Arc Discharge Method
- Laser Ablation Method
- Chemical Vapour Deposition

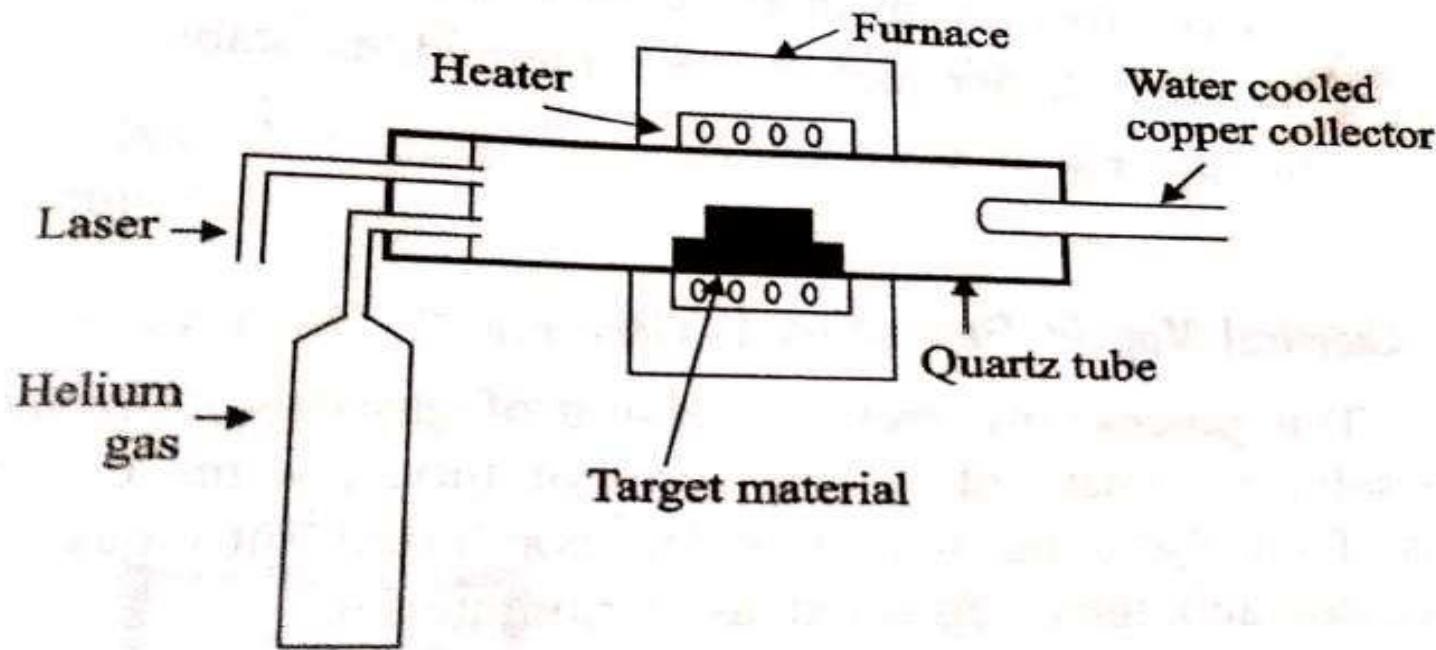


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## SYNTHESIS OF CNTS - Laser Ablation Method

In laser ablation technique, high power laser pulse is used to evaporate the material from the target. The stoichiometry of the material is protected in the interaction. The total mass ablated from the target per laser pulse is referred as ablation rate.





## SYNTHESIS OF CNTS

This method involves vaporization of target material containing small amount of catalyst (Ni or Co) by passing an intense pulsed laser beam at a higher temperature to about  $120^{\circ}\text{C}$  in a quartz tube reactor. Simultaneously an inert gas such as argon, helium is allowed to pass into the reactor to sweep the evaporated particles from the furnace to the colder collector.

### Uses:

- Nanotubes having a diameter of 10 to 20 nm and 100 micrometer can be produced by this method.
- Ceramic particles and coating can be produced.
- Other materials like silicon and carbon can also be converted into nanoparticles by this method



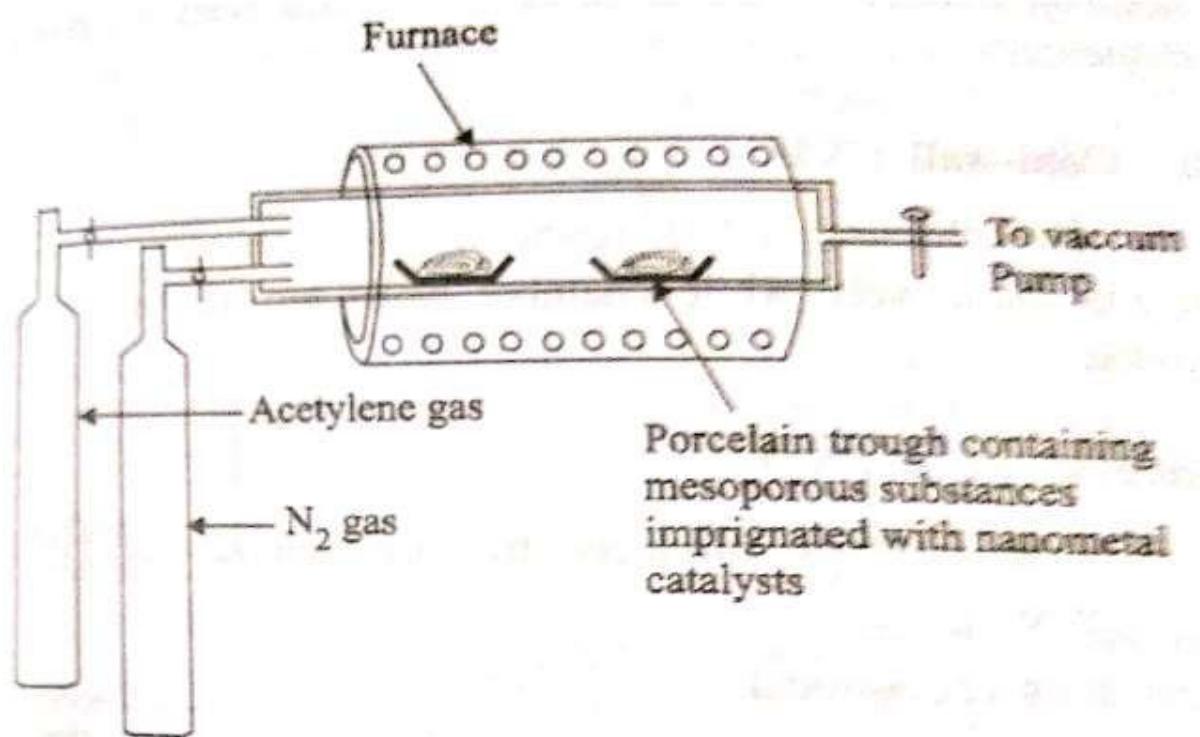
## SYNTHESIS OF CNTS - Chemical Vapour Deposition

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This process involves the conversion of gaseous molecules into solid nanomaterials in the form of tubes, wires or thin films.

Initially, the solid materials are converted into gaseous molecules and then deposited as nanomaterials.





## SYNTHESIS OF CNTS - Chemical Vapour Deposition

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The CVD reactor consists of a higher temperature vacuum furnace maintained at inert atmosphere. The solid substrate containing catalyst like Ni, Co, Fe supported on a substrate material like silica, quartz is kept inside the furnace. The hydrocarbons such as ethylene, acetylene and nitrogen cylinders are connected to the furnace. Carbon atoms produced by the deposition at  $1000^{\circ}\text{C}$ , condense on the cooler surface of the catalyst. As this process is continuous, CNT is produced continuously.

### Advantages

Nanomaterials produced from this method are highly pure, defect free and economical.



## APPLICATIONS OF CNTS

- Energy Storage (CNT forest)
- Solar cell electrode (CNT Network)
- Atomic Force Microscope (AFM)
- Super hydrophobic surface

### Uses of CNTs

- It is used in battery technology and in industries as catalyst.
- It is used as light weight shielding materials for protecting electronic equipments.
- It is used effectively inside the body for drug delivery
- It is used in composites, Ics.
- It can act as a very good biosensors,



# PHYSICAL VAPOUR DEPOSITION

Nanomaterials in the form of thin films, multilayer films, nanoparticles and nanotubes can be produced by physical vapour deposition methods.

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## Definition

Physical Vapour Deposition (PVD) is a technique by which a metal, ceramic or a compound can be converted into gaseous form and then deposited on the surface of a substrate.

In general, PVD methods are subdivided into:

1. Evaporation
2. Sputtering
3. Pulsed Laser Deposition or Laser Ablation

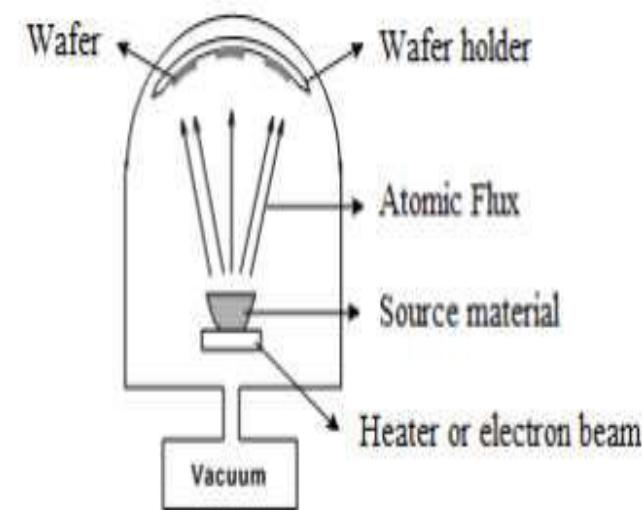


# PHYSICAL VAPOUR DEPOSITION - PVD

## EVAPORATION

The source materials used in this process are generally refractory metals such as W (Tungsten), Ta (Tantenum), Mo (Molybdenum) etc. In evaporation technique, both substrate and source materials (to be deposited) are placed inside the vacuum chamber ( $10^{-6}$  to  $10^{-7}$  torr). The vacuum is required to allow the molecules to evaporate and to move freely in the chamber.

An electron gun (e-gun) is used to produce electron beam of 10 keV. This beam is directed at the source material in order to develop sufficient vapour so as to produce deposits on wafer or substrates. Figure shows the schematic diagram of evaporation equipment.



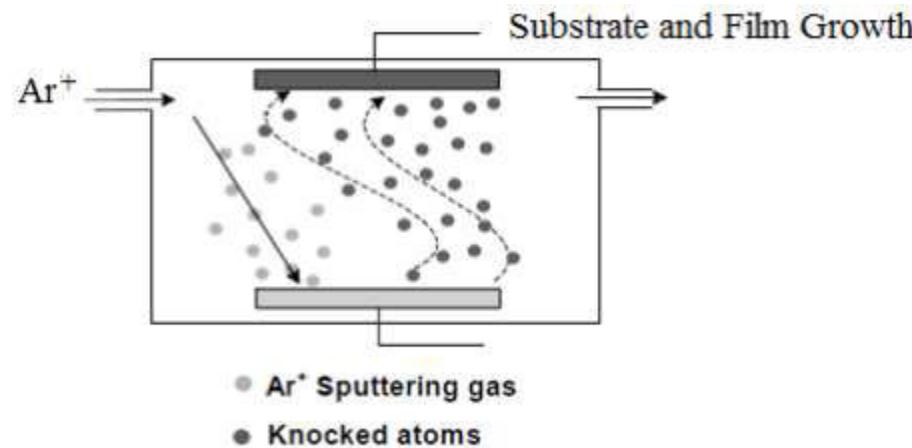


# PHYSICAL VAPOUR DEPOSITION

## SPUTTERING

The source materials used in this process are generally an alloy, ceramic or a compound. In sputtering technique, a high energy atom in ionized form usually  $\text{Ar}^+$  is used to hit the surface atoms of the targeted source material. Then the knocked out atoms in vapour form are deposited on the surface of the substrate to produce a uniform coatings.

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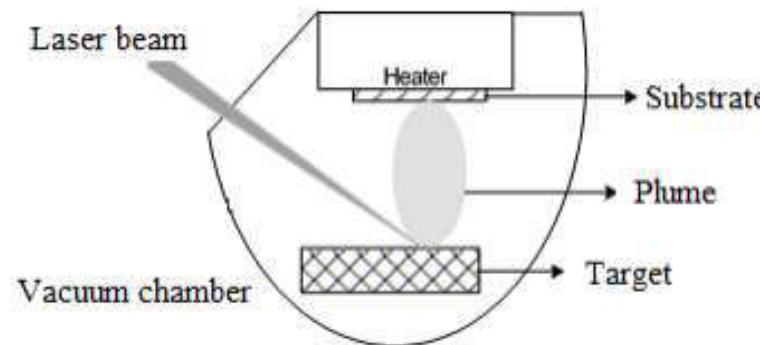




# PHYSICAL VAPOUR DEPOSITION

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Pulsed Laser Deposition or Laser Ablation Pulsed Laser Deposition (PLD) is a thin film deposition technique that is used to deposit materials on substrates. A base system consists of a target, substrate carrier which is mounted in a vacuum chamber. An excimer laser is used to energize the surface of a target to produce a deposition plume. The plume is typically directed towards the substrate where a thin-film is deposited. Since each shot of the laser is directly related to the amount of material ablated, the deposition rate can be calibrated and controlled very precisely. Figure.1.9 shows the schematic diagram of pulsed laser deposition.





# PHYSICAL VAPOUR DEPOSITION

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## Advantages

- Ultrapure films or particles can be produced by PVD since it uses a vacuum environment.
- PVD can provide good structural control by careful monitoring of the processing conditions.
- Materials can be deposited with improved properties compared to the substrate material.
- Almost any type of inorganic material can be used as well as some kinds of organic materials.
- The process is more environmental friendly than processes such as electroplating.



# PHYSICAL VAPOUR DEPOSITION

## Applications

PVD is used to produce the deposit of various metals, alloys or compounds in the form of coatings or films for: Optics (Ex: Antireflection coatings) Electronics (Ex: Metal contacts) Mechanics (Ex: hard coatings on tools) etc.

PVD coatings are generally used to improve hardness, wear resistance and oxidation resistance.



## APPLICATIONS OF CNTs

**Energy storage:** Nanotubes are used for energy storage (fuel cells, batteries) due to small dimensions, smooth surface topology and perfect surface specificity. The efficiency of fuel cells is determined by the electron transfer rate at the electrodes which is fastest on nanotubes.

**Hydrogen storage:** On combustion it produces water. Hydrogen is stored in gas phase and electrochemical adsorption CNT is cylindrical, hallow geometry and extremely small in diameter. Hence hydrogen can be stored in the inner core of CNT through capillary effect.

**Electrochemical Super capacitors:** Super capacitors have high specific capacitance and potentially applicable in electronic devices Two electrodes separated by an ionic insulating material.

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# METHODS OF CHARACTERIZATION OF NANO MATERIALS

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- X-Ray Diffraction Method (XRD)
- High Resolution - Scanning Electron Microscope (HR-SEM)
- High Resolution - Transmission Electron Microscope (HR-TEM)
- Atomic Force Microscopy (AFM)
- X-ray photoelectron spectroscopy (XPS)
- Fourier Transform-Raman Spectroscopy (FTRAMAN)
- Thermo Gravimetric –Differential Thermal Analysis (TG-DTA)
- Energy Dispersive X-ray spectroscopy (EDAX)
- Selected Area Electron Diffraction (SAED)



# METHODS OF CHARACTERIZATION OF NANO MATERIALS

## X-Ray Diffraction Method (XRD)

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- Amorphous or Crystalline Structure (crystal) of the materials
- If Intensity peaks are sharp then structure is well ordered
- If the intensity peaks are broad then Material is NANO (crystallite size is nano)
- Crystallite Size is calculated using Debye-Scherrer formula

$$\text{Crystallite Size} = \frac{0.94 \lambda}{\beta \cos \theta}$$

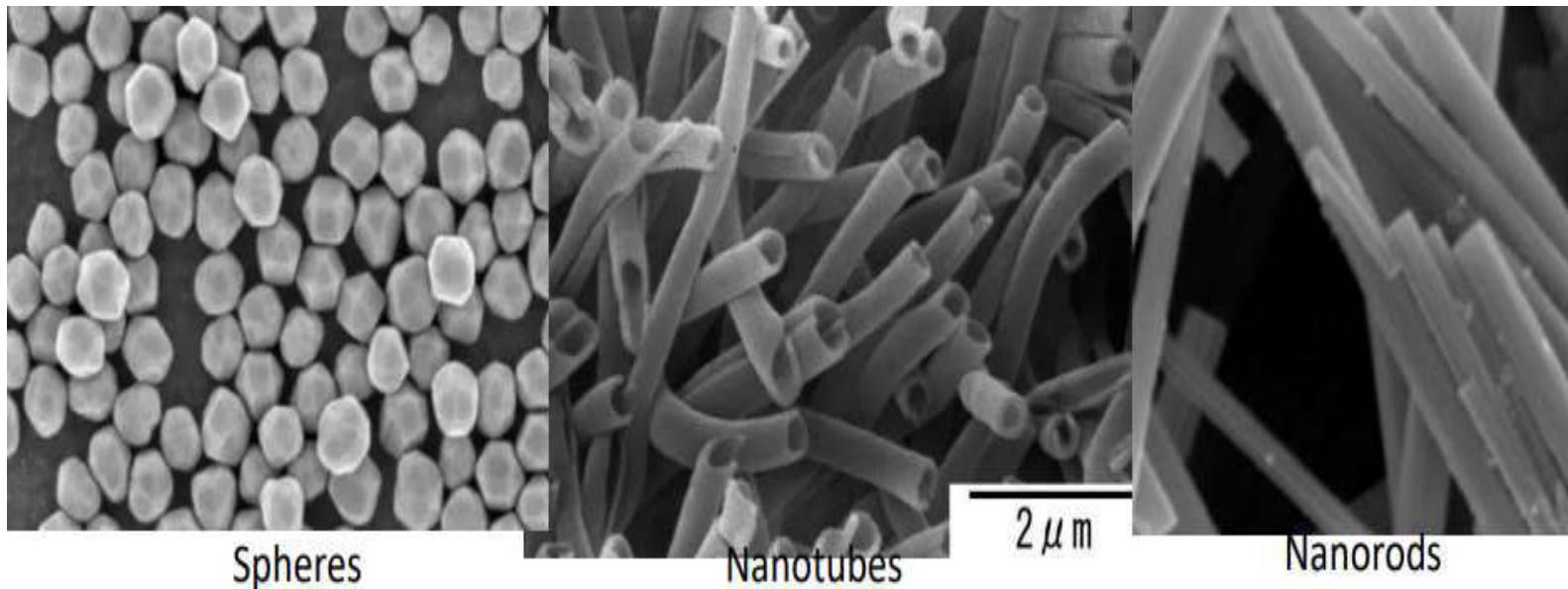
- Beta is the Full Width – Half maximum
- Composition of the material identified and compared with JCPDS, each peak is indexed .



# High Resolution - Scanning Electron Microscope (HR-SEM)

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- SEM is used to analyze the surface of the object
- Topography – surface features like texture hardness etc
- Morphology - Shape and size of the nanoparticle
- SEM can resolve object as close as 20nm

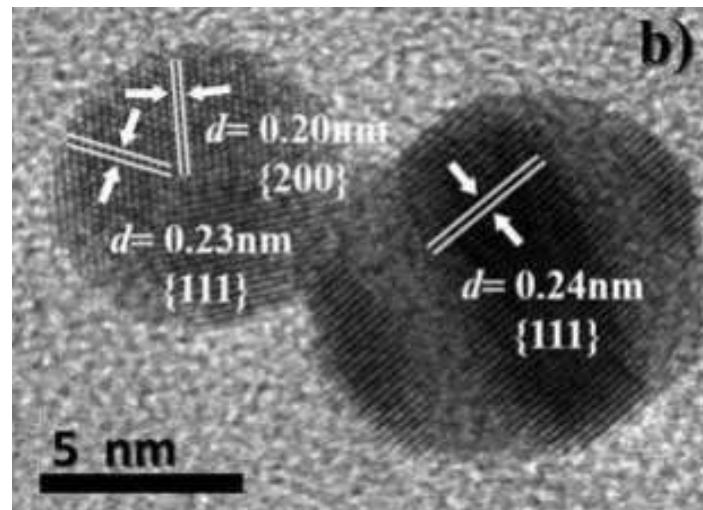




# Transmission Electron Microscope (HR-TEM)

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- TEM provides information about the inner structure of the sample
- Morphology - Shape and size of the nano particle
- Composition – Elemental composition
- Crystallographic info – Atomic arrangements in the sample
- TEM can resolve object as close as 1 nm – Atomic resolution and inter planar distance can be viewed as fringes.



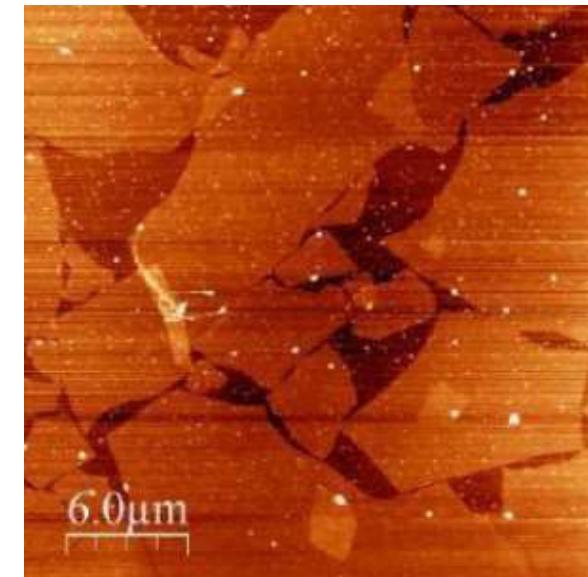
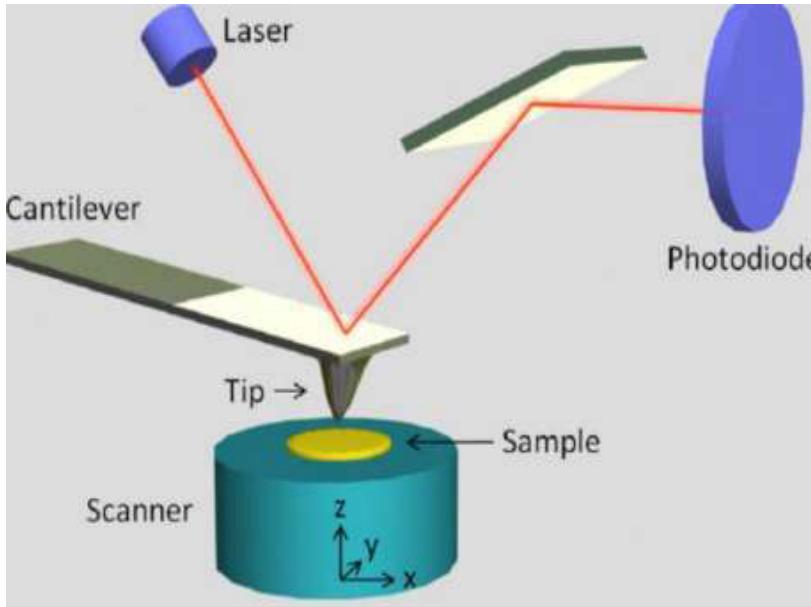


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## ATOMIC FORCE MICROSCOPY (AFM)

- AFM is based on cantilever/tip interactions with the sample.
- Cantilever/tip (Probe) moves up and down or side-by side motion.
- AFM tip scans along the surface of the sample.
- Particle size of nanomaterials are evaluated.





**Bharath**  
INSTITUTE OF HIGHER EDUCATION AND RESEARCH  
(Declared as Deemed - to - be - University under section 3 of UGC Act 1956)



# SEMICONDUCTOR PHYSICS

## UNIT - I

**PRESENTED BY**

**DR. C. RATHIKA THAYA KUMARI,**

Associate Professor,

Department of Physics



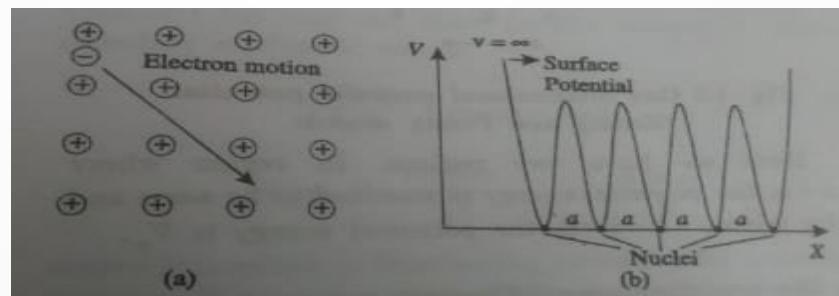
## Band Theory or Zone Theory

- The free electron theories failed to explain why some solids are conductors, insulators and semiconductors.
- A solution to this problem was given by band theory of solids.
- According to free electron theory, the potential energy of an electron inside the crystal is constant (zero). So it can move freely inside the crystal and is restrained only by the surface of the crystal.



## Postulates of Band Theory

- According to band theory, potential energy of an electron within the crystal is periodic due to periodicity of the crystal. i.e. free electrons move inside periodically in the lattice.
- The potential energy of the solid varies periodically with the periodicity of space lattice.
- It is assumed that the potential energy of the electron at the positive ion site is zero and is maximum when it is half way between the adjacent nuclei.





## Brillouin Zone

Brillouin zones are defined as the boundaries in a crystal lattice that are marked by the values of propagation wave vector in which the electrons can have allowed energy values without diffraction.

The relation between wave vector and the energy of an electron in a constant potential field is given by,  $E = n^2 h^2 / 8ma^2$

$$\text{The wave vector } K = n\pi / a$$

$$\text{From this, } a = n\pi / K$$

Substituting in E, we get  $E = K^2 h^2 / 8\pi^2 m$

- Also,  $K = \pm \pi/a, \pm 2\pi/a, \pm 3\pi/a\dots$

If we plot a graph between E and K, the curve obtained is in the form of parabola with discontinuities.

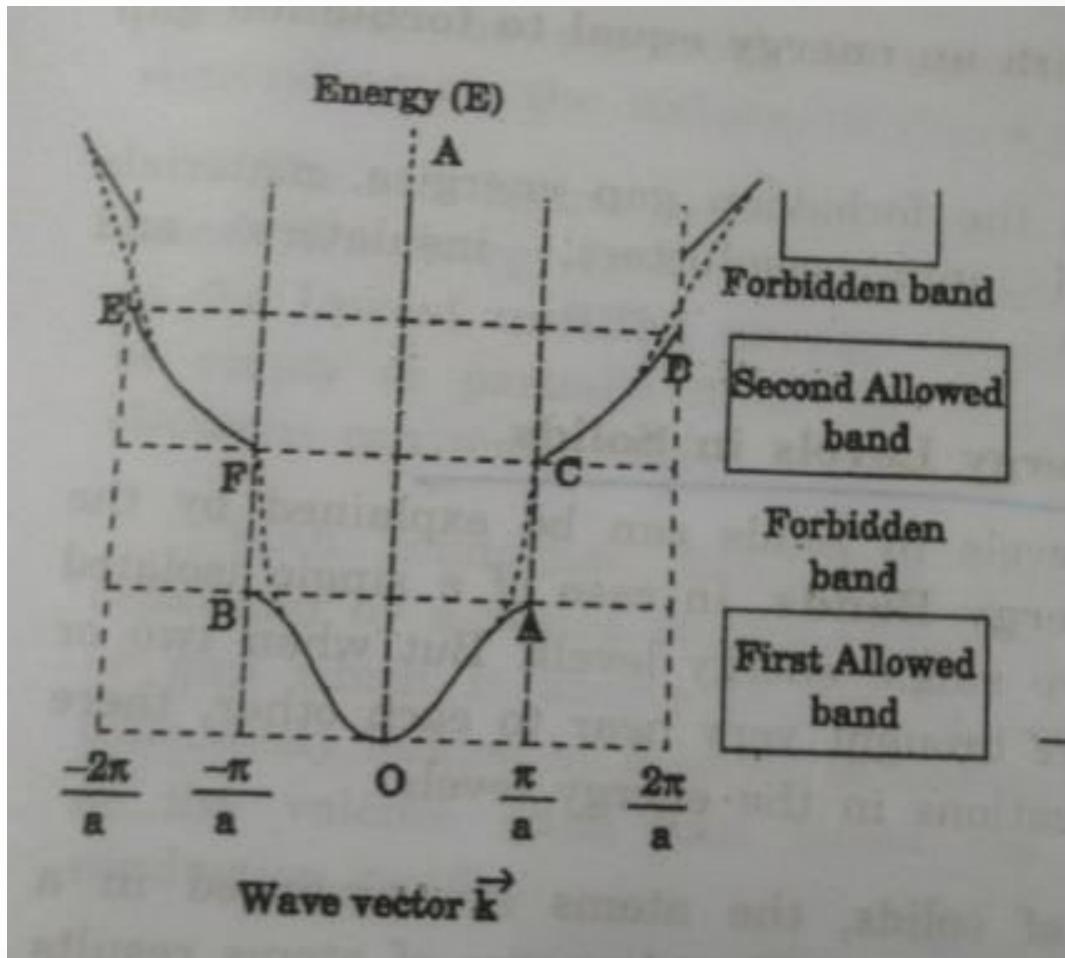


## Brillouin Zone

From the graph, it is seen that the energy of an electron increases continuously from 0 to  $\pm \pi/a$ , then the electron meets the wall and is reflected.

This range of allowed energy values in the region between  $-\pi/a$  to  $+\pi/a$  is

called **first Brillouin zone**





## Brillouin Zone

The second allowed energy value consists of two parts. One energy value from  $\pi/a$  to  $2\pi/a$  and another from  $-\pi/a$  to  $-2\pi/a$ , which is called **second Brillouin zone**.

Similarly, there will be 3<sup>rd</sup>, 4<sup>th</sup> etc. Brillouin zones for various ranges for different k values.

Also, each Brillouin zone is separated by break up energy values known as **forbidden zone or Energy gap**.

Thus, we conclude that the electrons can go from one Brillouin zone to the other only when it is supplied with an energy equal to forbidden gap energy.



## Origin of Energy Levels in Solids

Energy levels in solids can be explained by the concept Energy Bands.

In case of solids, the atoms are arranged in a systematic space lattice. The closeness of atoms results in the intermixing of electrons of neighboring atoms.

Due to this intermixing, the number of permissible energy levels increases, as a result the electrons are free to move in increased energy levels of the atoms which in turn increases the conduction of the solids.

A set of closely spaced energy levels is called an energy band.



## Origin of Energy Levels in Solids

Valence Band: The electrons in the outermost shell are called valence electrons. The band formed by a series energy level containing the valence electrons is known as **Valence band**. Thus, it is defined as a band which is occupied by the **valence electrons**. The valence band may be **partially or completely filled** up depending on the nature of the material.

Conduction Band: The next higher permitted band is the conduction band.

The conduction band energy levels are defined as the **lowest unfilled energy band**. This band may be **empty or partially filled**. Here the electrons can move freely.

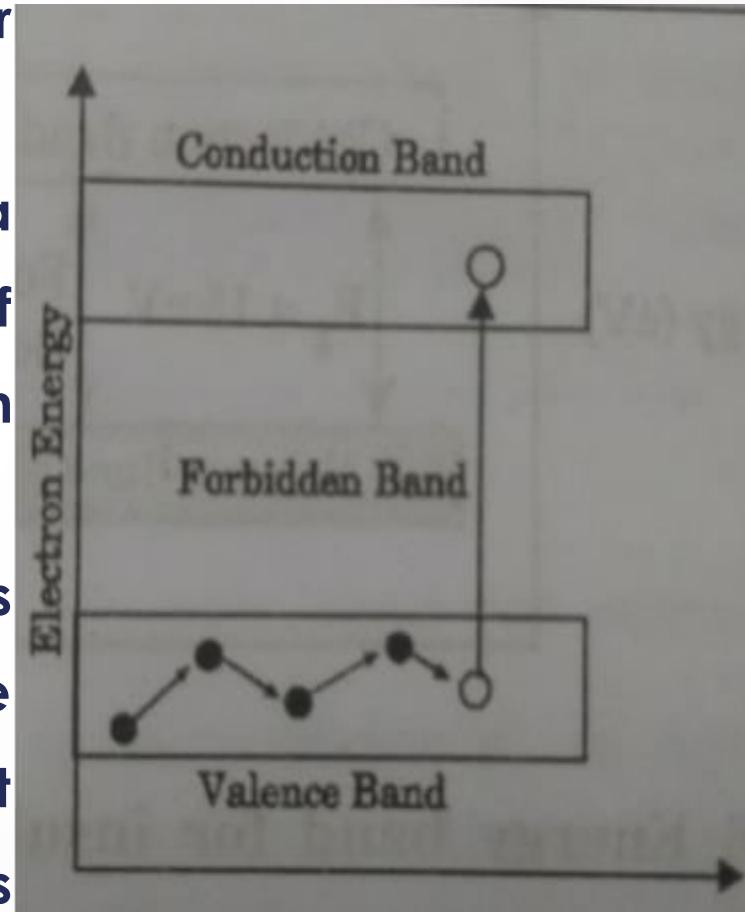


# Origin of Energy Levels in Solids

The conduction band and valence band are separated by a region or gap known as **forbidden band**.

This band is collectively formed by a series of energy levels above the top of valence band and below the bottom of conduction band.

Hence, no electron can exist in this band. When an electron in the valence band absorbs enough energy, it crosses the forbidden gap and enters into the conduction band.



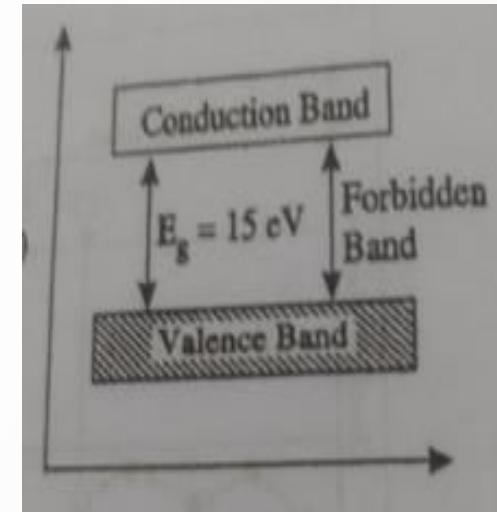


# Classification of Electronic Materials

Based on the magnitude of forbidden gap, the solids are classified into insulators, semiconductors and conductors.

## Insulators:

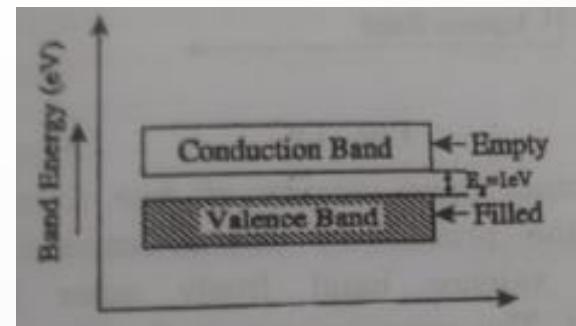
- At 0K, the valence band is completely filled and conduction band is empty.
- The forbidden energy band is very wide.
- The electrons cannot jump from valence band to conduction band because the valence electrons are very tightly bounded to the atoms.
- Even in the presence of electric field, the electrons cannot jump from valence band to conduction band.





## Semiconductors

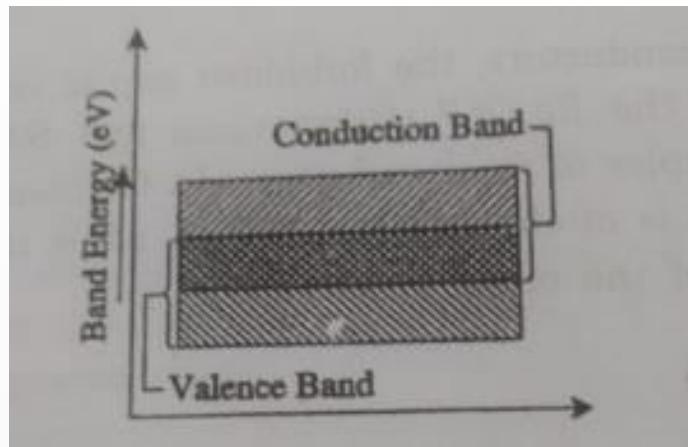
- The forbidden gap is very small. For Germanium it is 0.7 eV & for Silicon it is 1.1 eV.
- The electrical properties of semiconductors lies between conductors and insulators.
- At 0K, there are no free electrons in conduction band but valence band is completely filled.
- When a small amount of energy is supplied, the electrons can easily jump from valence band to conduction band , since the forbidden gap is very small.





## Conductors

- In conductors, there is no forbidden gap, because the valence band and conduction bands overlap each other.
- In the conduction band, plenty of free electrons are present for electrical conduction.
- The electrons from valence band freely enter into the conduction band.
- The total current in conductors is only due to the flow of electrons.





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# SEMICONDUCTOR PHYSICS

## UNIT - I

**PRESENTED BY**

**DR. C. RATHIKA THAYA KUMARI,**

Associate Professor,

Department of Physics



## FERMI ENERGY AND ITS IMPORTANCE

- Fermi energy level is the maximum energy level upto which the electrons can be filled at 0K.
- Thus, it acts as a reference level which separates the vacant and filled states at 0K.
- At 0K, below Fermi energy level electrons are filled and above that it is empty.
- When the temperature is increased, few electrons gain thermal energy and it goes to higher energy states.



## FERMI DISTRIBUTION FUNCTION

The probability of an electron occupying in a given energy state  $E$ . It is a probability distribution function.

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

The probability value  $F(E)$  lies between 0 and 1.

- If  $F(E) = 1$ , the energy level is occupied by an electron.
- If  $F(E) = 0$ , the energy level is vacant.
- If  $F(E) = 1/2$ , there is a 50% chance for the electron occupying in that energy level.



## EFFECT OF TEMPERATURE ON FERMI FUNCTION

The dependence of Fermi distribution function on temperature and its effect on the occupancy energy levels are discussed here:

**Case (i) Probability of occupation for  $E < E_F$  at  $T = 0$**

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

**When  $T=0K$  and  $E < E_F$ ,  $F(E) = 1$**

At  $T=0K$ , there is 100% chance for the electrons to occupy the energy levels below the Fermi level i.e. below the Fermi energy level, all the levels are occupied with the electrons.



## EFFECT OF TEMPERATURE ON FERMI FUNCTION

**Case (ii)** Probability of occupation for  $E > E_F$  at  $T = 0$

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

**When  $T=0K$  and  $E > E_F$ ,  $F(E) = 0$**

At  $T=0K$ , there is 0% chance for the electrons to occupy the energy levels above the Fermi level i.e. all the energy levels above the Fermi energy level, all the levels are not occupied with the electrons.



## EFFECT OF TEMPERATURE ON FERMI FUNCTION

**Case (iii)** Probability of occupation at ordinary temperature

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

At ordinary temperature, the value of probability starts reducing from 1 for values of E slightly less than  $E_F$ .

When  $T > 0K$ , the Fermi function  $F(E)$  varies with  $E$ , as shown in Figure.

At any temperature other than 0K and  $E = E_F$ ,

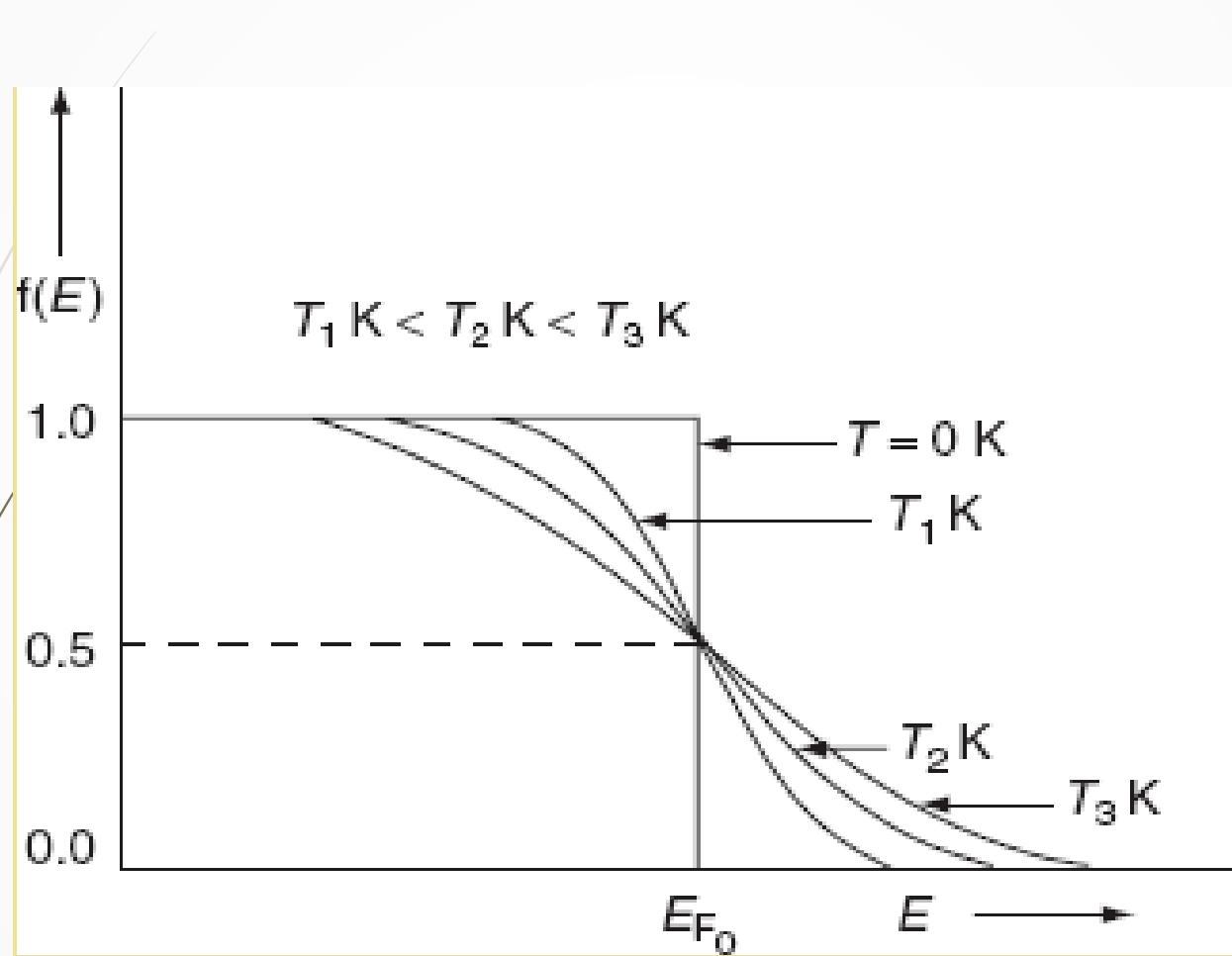
$$F(E) = 1 / 2 = 0.5 = 50\%$$

Hence, there is a 50 % chance for the electrons to occupy Fermi energy level, at  $E = E_F$ .

Further for  $E > E_F$ , the probability value falls off rapidly to zero.



## EFFECT OF TEMPERATURE ON FERMI FUNCTION





## UNIT I - CONTENTS

### UNIT I

Classical Free electron theory-Quantum Free electron theory-Density of states-Energy band in solids  
-Kronig-Penney model-Basics of experimentation-E-k diagram-Direct and Indirect band gap-Concept of phonons-Concept of Brillouin Zone-Energy band structure of semiconductor-Brillouin zone  
Concept of effective mass- -Classification of electronic materials-Fermi level-Probability of occupation-Influence of donors in semiconductor-Influence of acceptors in semiconductor-Non-equilibrium properties of carriers (Contact Hours-14)



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# SEMICONDUCTOR PHYSICS

## UNIT - I

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# INTRODUCTION



- The electron theory aims to explain the structure and properties of solids through their electronic structure.
- According to this theory a metal can be considered to consist of ion cores having the nucleus and electrons other than valence electrons.
- These valence electrons form an electron gas surround the ion cores and are free to move anywhere within the metals.



- The electron theory of solids has been developed in three main stages

1) **Classical free electron theory:** Drude and Lorentz developed this theory in 1900 . According to this theory metal containing free electron obey the laws of classical mechanics.

2) **Quantum free electron theory:** Sommerfeld developed this theory during 1928. According to this theory, the free electrons obey quantum laws.

### **iii). The Zone theory:**

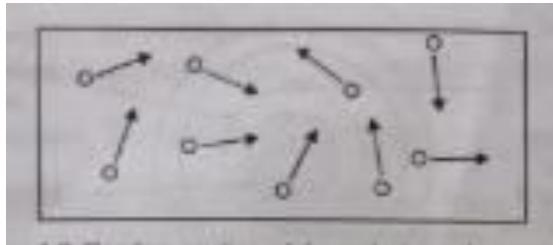
Bloch stated this theory in 1928. According to this theory, the free electrons move in a periodic field provided by the lattice. This theory is also called “Band theory of solids”.



# CLASSICAL FREE ELECTRON THEORY

## POSTULATES

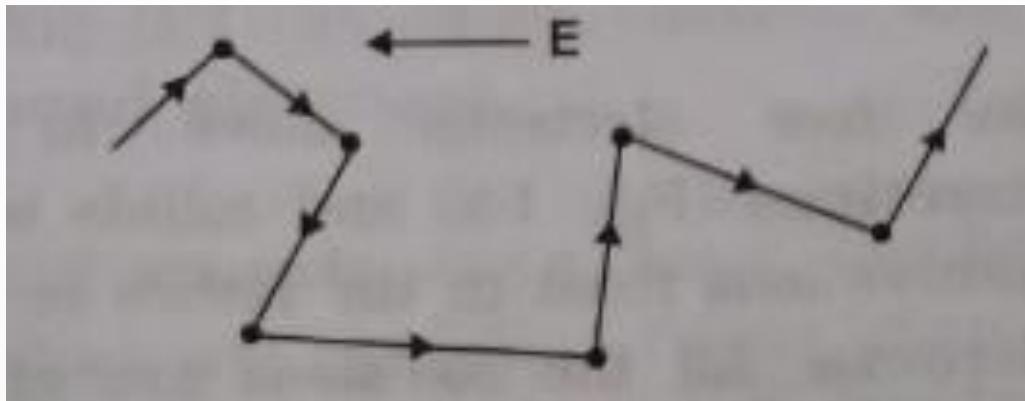
- The free electrons in metals, move freely or randomly in all possible directions, in the absence of electric field



- While moving, the free electrons collide with each other and also with the lattice elastically without any loss in energy.
- The force between electrons and ion core is negligible, hence its total energy is only kinetic not potential.

## POSTULATES

- When an external field is applied, the free electrons moves in a direction opposite to the electric field.
- As a result, these free electrons may acquire a constant velocity called drift velocity.





# DEFINITIONS

## DRIFT VELOCITY

The average velocity acquired by the free electron in a particular direction, due to the application of electric field is called drift velocity.

## MOBILITY

The drift velocity acquired by the free electron per unit electric field applied to it.

$$\text{Mobility} = \text{Drift velocity} / \text{Electric field}$$

# DEFINITIONS

## RELAXATION TIME

**It is the time taken by the free electrons to reach its equilibrium position from its disturbed position in the presence of electric field.**

## MEAN FREE PATH

**The average distance travelled between two successive collisions are called mean free path.**



## **DRAWBACKS OF CLASSICAL FREE ELECTRON THEORY**

- It is a **macroscopic** theory
- Classical theory states that all free electrons absorb energy, but quantum theory states that only few electrons absorb energy.
- Classical theory cannot explain compton effect, photoelectric effect, blackbody radiation etc. but these concepts are completely based on quantum theory.
- The electrical conductivity and resistivity of a semiconductors and insulators are not explained by classical theory but band theory clearly explains these concepts successfully for all solids.



# QUANTUM FREE ELECTRON THEORY

The drawbacks of classical theory can be rectified using quantum theory. The problem was approached using Fermi-Dirac statistics.

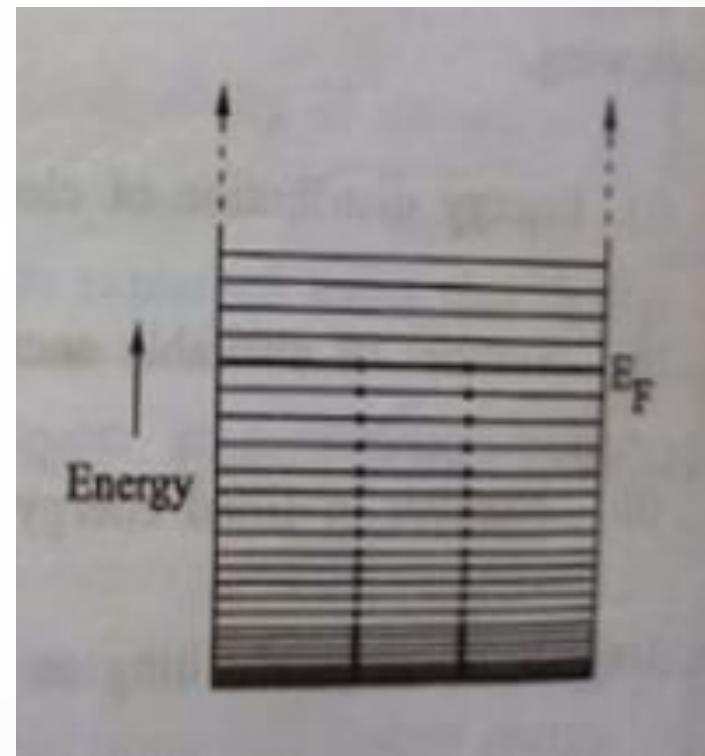
## ASSUMPTIONS

- Classical theory – Kinetic Energy of an electron is Zero at 0K.
- Quantum theory – The electrons arrangement in an energy level is clearly explained by knowing the following terms:
  - Energy distribution of an electron
  - Number of available energy states
  - Number of filled energy states
  - Probability of filling an electron in an energy state



## ENERGY DISTRIBUTION OF ELECTRONS IN A METAL

- The energy levels are discrete.
- The space between two energy levels is very less ( $10^{-6}$  eV).
- The distribution of energy levels seems to be continuous.
- Each energy level can provide only two states, one for spin up and the other for spin down.  
Thus 2 electrons can be filled in each energy state.  
If there N number of electrons means,  $N/2$  number of energy states.
- This  $(N/2)$ th level is the highest filled energy level, called **Fermi Energy Level**.





## FERMI ENERGY AND ITS IMPORTANCE

- Fermi energy level is the maximum energy level upto which the electrons can be filled at 0K.
- Thus, it acts as a reference level which separates the vacant and filled states at 0K.
- At 0K, below fermi energy level electrons are filled and above that it is empty.
- When the temperature is increased, few electrons gain thermal energy and it goes to higher energy states.



## FERMI DISTRIBUTION FUNCTION

The probability of an electron occupying in a given energy state  $E$ . It is a probability distribution function.

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

(2.7)

$E_F$  = Fermi energy or Fermi level

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

$T$  = absolute temperature in K

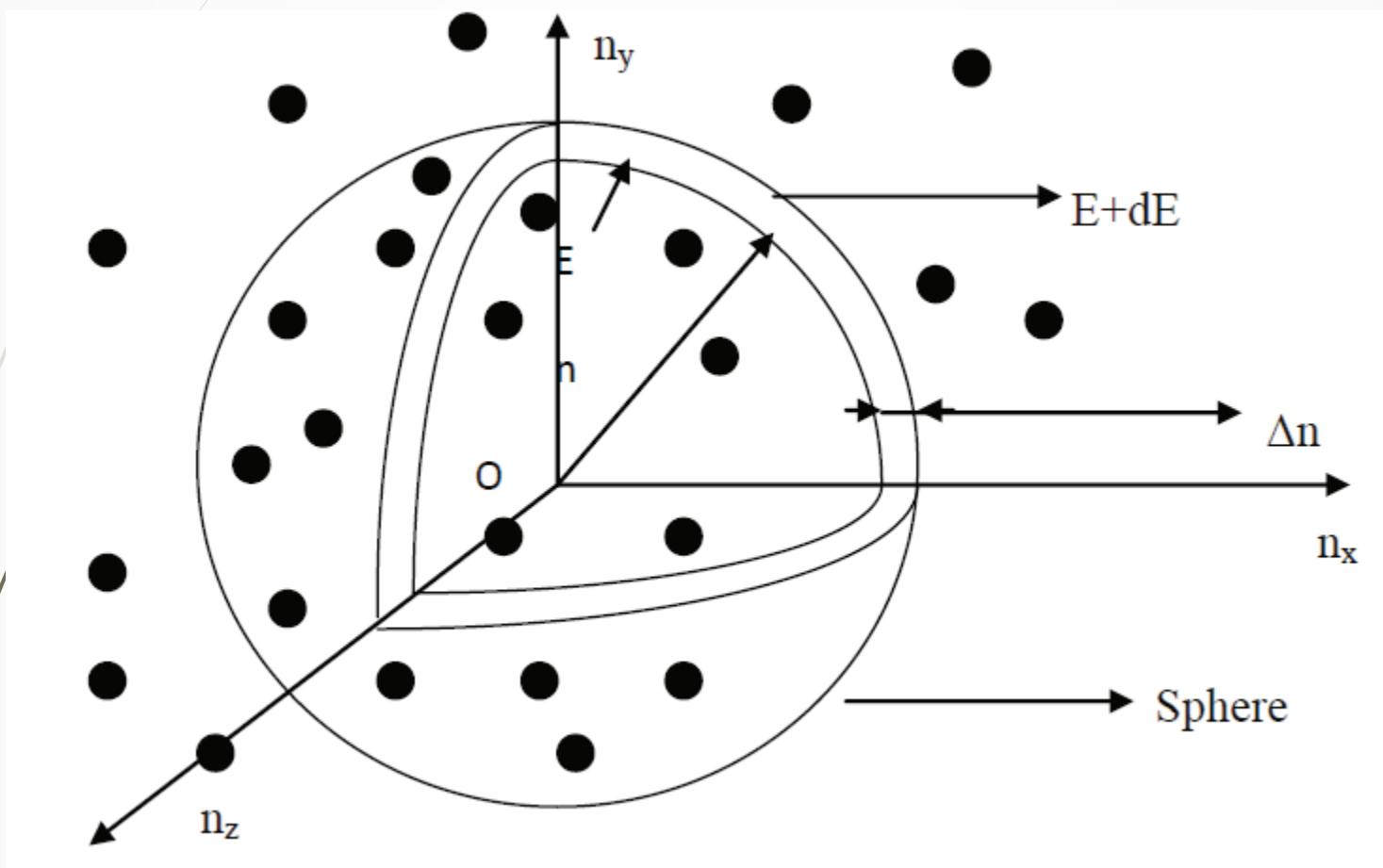


# DENSITY OF STATES IN METALS

- **Fermi function** – Probability of filling of electrons in an energy state.
  - It does not give information about the number of electrons that can be filled in an energy state.
- The number of available energy states are called as **density of states**.
- **Density of states** is defined as the number of available electrons per unit volume in an energy interval.



# DENSITY OF STATES IN METALS





## DENSITY OF STATES IN METALS

Density of States  $\Sigma(E) dE$  is defined  
as the number of available electron states  
per unit volume in an energy interval  $dE$ .

$$\left. \begin{array}{l} \text{Number of Energy states} \\ \text{within the sphere} \end{array} \right\} n = \frac{4}{3} \pi n^3.$$

Since  $n_x, n_y, n_z$  takes Positive Values, we  
should consider only  $(1/8)^{\text{th}}$  of the sphere Volume.



## DENSITY OF STATES IN METALS

∴ Number of available Energy states within the sphere,  $n = \frac{1}{8} \left[ \frac{4}{3} \pi n^3 \right]$  of radius  $n$  is, —————— ①

Similarly,

Number of available Energy states within the sphere of radii  $n+dn$  is,  $= \frac{1}{8} \left[ \frac{4}{3} \pi (n+dn)^3 \right]$  —————— ②

∴ Number of available Energy states b/w  $E$  &  $E+dn$  is,  $= \frac{1}{8} \left[ \frac{4}{3} \pi (n+dn)^3 - \frac{4}{3} \pi n^3 \right]$

Number of available Energy states b/w  $dE$  is,  $= \frac{1}{8} \left[ \frac{4}{3} \pi (n^3 + dn^3 + 3n^2 dn + 3n dn^2 - \cancel{\frac{4}{3} n^3}) \right]$



## DENSITY OF STATES IN METALS

Since the higher terms of  $d_n$  is very small,  
 $d_n^2 \text{ and } d_n^3$  can be neglected.

$$\therefore Z(E) dE = \frac{1}{8} \cdot \frac{4}{3} \pi \cdot 3n^2 dn$$

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

We know,  
Energy of an electron,  $E = \frac{n^2 h^2}{8m l^2}$  --- (4)

$$n^2 = \frac{8ml^2 E}{h^2} \quad \text{--- (5)}$$

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



## DENSITY OF STATES IN METALS

Diff. eqn(5) ,

$$2n dn = \frac{8\pi l^2}{h^2} \cdot dE$$

$$ndn = \frac{8\pi l^2}{2h^2} dE \quad \text{--- } 7$$

Eqn (3) Can be written as ,

$$\Sigma(E) dE = \frac{\pi}{2} n(ndn) \quad \text{--- } 8$$



## DENSITY OF STATES IN METALS

Eqn (3) can be written as,

$$Z(E) dE = \frac{\pi}{2} n (ndn) \quad \text{--- (8)}$$

Subs eqn (6) & (7) in eqn (8),

$$Z(E) dE = \frac{\pi}{2} \cdot \left[ \frac{8ml^2 E}{h^2} \right]^{1/2} \cdot \left[ \frac{8ml^2}{2h^2} \right] dE.$$

$$= \frac{\pi}{2} \cdot \frac{1}{2} \left[ \frac{8ml^2}{h^2} \right]^{3/2} \cdot E^{1/2} dE.$$

$$Z(E) dE = \frac{\pi}{4} \left[ \frac{8ml^2}{h^2} \right]^{3/2} E^{1/2} dE.$$

$$Z(E) dE = \frac{\pi}{4} \left[ \frac{8m}{h^2} \right]^{3/2} \cdot l^3 E^{1/2} dE \quad \text{--- (9)}$$



## DENSITY OF STATES IN METALS

If  $l^3 = 1$ , then eqn (9) becomes,

$$Z(E)dE = \frac{\pi}{4} \left[ \frac{8m}{h^2} \right]^{3/2} \cdot E^{1/2} dE \quad \text{--- (10)}$$

Since each energy level provides two electrons

Then,  $Z(E)dE = 2 \times \frac{\pi}{4} \left[ \frac{8m}{h^2} \right]^{3/2} E^{1/2} dE$

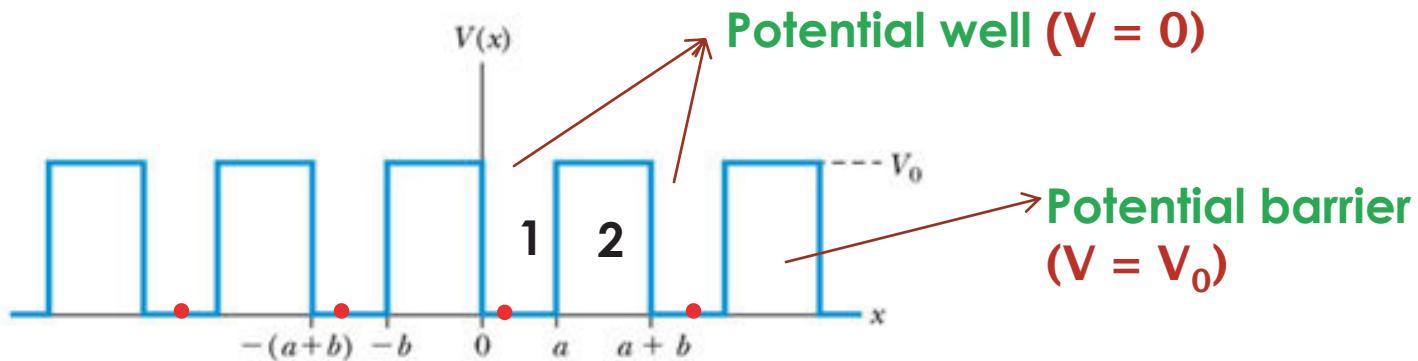
$$Z(E)dE = \frac{\pi}{2} \left[ \frac{8m}{h^2} \right]^{3/2} E^{1/2} dE \quad \text{--- (11)}$$

Eqn (11) represents the number of available energy states per unit volume.



## Kronig - Penny Model

- The Kronig-Penney model demonstrates that a simple one-dimensional periodic potential yields energy bands as well as energy band gaps.
- The potential assumed is shown as below



- represents the positive ion core

In the **potential well** near the positive ion electron potential is zero i.e.  $V = 0$

In the **potential barrier** away from the positive ion electron potential is maximum i.e.  $V = V_0$



## Kronig - Penny Model

According to this theory, the electrons move in a periodic potential produced by the positive ion cores. The potential of the electron varies periodically with periodicity of the ion core and the potential energy of the electron is zero near the nucleus of the positive ion core and maximum when it is lying between the adjacent nuclei which are separated by the interatomic spacing ' $a$ '.



## Kronig - Penny Model

Applying the Schrodinger's Time Independent wave equation for the above two regions,

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

for I in the diagram,  $V=0$

$$\frac{d^2\psi}{dx^2} + \frac{2mE}{\hbar^2} \psi = 0 \rightarrow ① \quad \text{for } 0 < x < a$$

for II in the diagram,  $V=V_0$

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} (E-V_0) \psi = 0 \rightarrow ② \quad \text{for } -b < x < 0$$

$$\text{Put } \alpha^2 = \frac{2mE}{\hbar^2}, \beta^2 = -\frac{2m}{\hbar^2} (E-V_0)$$



## Kronig - Penny Model

Substituting the value of  $\alpha$  and  $\beta$ ,

Then equations ① and ② becomes

$$\frac{d^2\psi}{dx^2} + \alpha^2\psi = 0 \rightarrow ③$$

$$\frac{d^2\psi}{dx^2} - \beta^2\psi = 0 \rightarrow ④$$

The solutions for Equations 3 and 4 can be given as,

$$\psi = e^{ikx} u_k(x) \rightarrow ⑤$$



## Kronig - Penny Model

differentiating ⑤ with respect to 'x'

$$\frac{d\psi}{dx} = \frac{d}{dx} e^{ikx} u_k(x)$$

$$\frac{d^2\psi}{dx^2} = e^{ikx} \frac{d}{dx} u_k(x) + u_k(x) \frac{d}{dx} e^{ikx}$$

$$\frac{d^2\psi}{dx^2} = e^{ikx} \cdot \frac{du_k}{dx} + u_k i k e^{ikx}$$

Again differentiating with respect to 'x'

$$\frac{d^3\psi}{dx^3} = e^{ikx} \cdot \frac{d^2 u_k}{dx^2} + \frac{du_k}{dx} (i k e^{ikx}) + i k \left[ u_k i k e^{ikx} + e^{ikx} \frac{du_k}{dx} \right]$$

$$\frac{d^3\psi}{dx^3} = e^{ikx} \frac{d^2 u_k}{dx^2} + i k e^{ikx} \frac{du_k}{dx} - k^2 u_k e^{ikx} + i k e^{ikx} \frac{du_k}{dx} \rightarrow ⑥$$



## Kronig - Penny Model

Put equ@ in equ ③

$$e^{ikx} \frac{d^2 U_k}{dx^2} + ik e^{ikx} \frac{dU_k}{dx} - k^2 U_k e^{ikx} + ik e^{ikx} \frac{dU_k}{dx} + \alpha^2 e^{ikx} U_k = 0$$

Divide the above equation with  $e^{ikx}$

$$\frac{d^2 U_k}{dx^2} + ik \frac{dU_k}{dx} - k^2 U_k + ik \frac{dU_k}{dx} + \alpha^2 U_k = 0$$

$$\frac{d^2 U_k}{dx^2} + 2ik \frac{dU_k}{dx} + (\alpha^2 - k^2) U_k = 0 \rightarrow ⑦$$

Put equ @ in ④ , we get

$$\frac{d^2 U_k}{dx^2} + 2ik \frac{dU_k}{dx} - (\beta^2 + k^2) U_k = 0 \rightarrow ③$$



## Kronig - Penny Model

The general solution for equations 7 & 8 can be given as,

$$U_1 = Ae^{i(\alpha-k)x} + Be^{-i(\alpha+k)x} \rightarrow ⑨$$

$$U_2 = Ce^{(\beta-i\kappa)x} + De^{-(\beta+i\kappa)x} \rightarrow ⑩$$

By solving above two equations , we get

$$\alpha + \beta = C + D$$

And solving the above equation at boundary conditions,

We get  $\frac{\alpha^2 + \beta^2}{\alpha\beta} \sinh\beta b \sin\alpha x + \cosh\beta b \cos\alpha x = \cos k(a+b)$

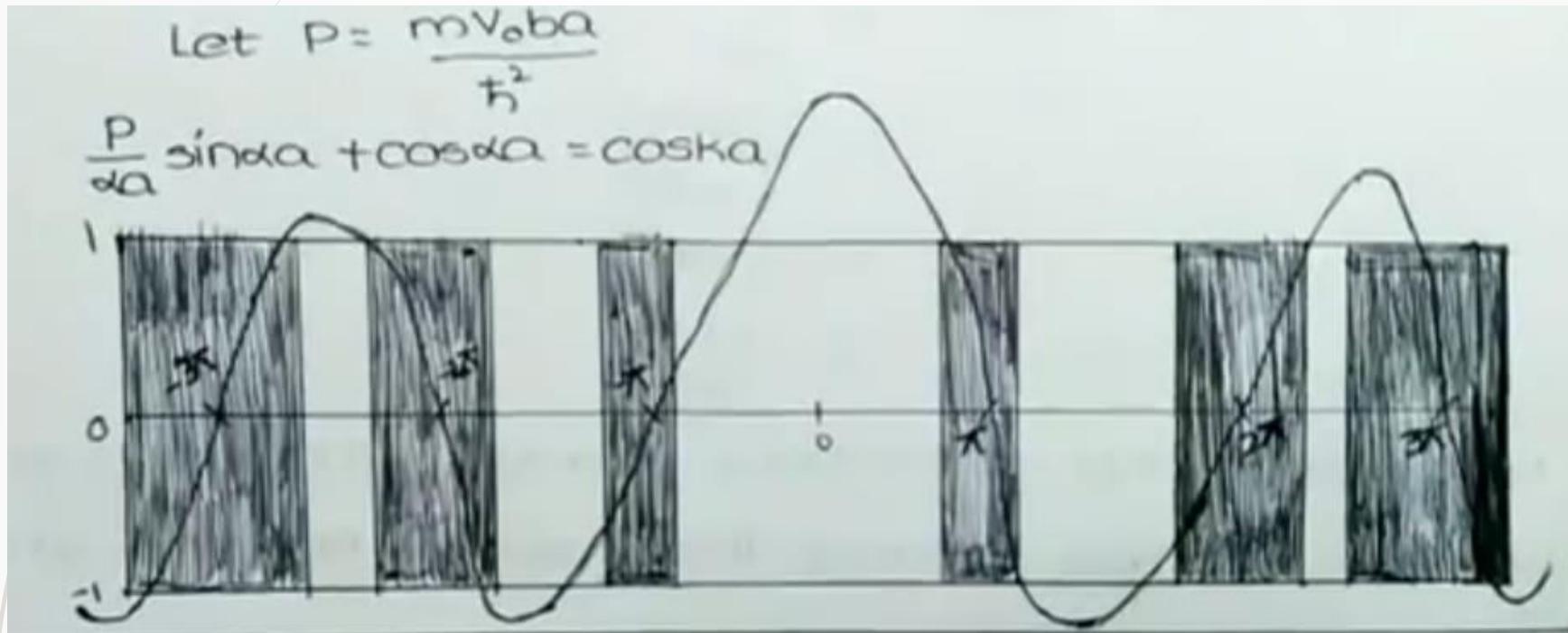
By solving we get,

$$\frac{mv_0b}{\alpha\hbar^2} \sin\alpha a + \cos\alpha a = \cos ka$$

$$\frac{mv_0ba}{\alpha a\hbar^2} \sin\alpha a + \cos\alpha a = \cos ka$$



## Kronig - Penny Model



- Shaded region represents the **Allowed Region** (-1 to +1)
- Non - Shaded region represents the **Forbidden Region**
- The discontinuity in energy occurs at the region at  $K = \pm \pi/a, \pm 2\pi/a, \pm 3\pi/a\dots$



## Discussion

➤ At P tends to infinity,  $\sin \alpha a = 0$ , i.e.  $\alpha a = n\pi$ ,  $\alpha = n\pi / a$ .

$$\text{Hence Energy } E = n^2\pi^2 / 8ma^2$$

In this case, the Energy levels are discrete

It is similar to a particle in a one dimensional potential box.

This indicates the nature of an insulator.

➤ At P tends to Zero,  $\cos \alpha a = \cos Ka$ ,

$$\text{Hence Energy } E = P^2 / 2m$$

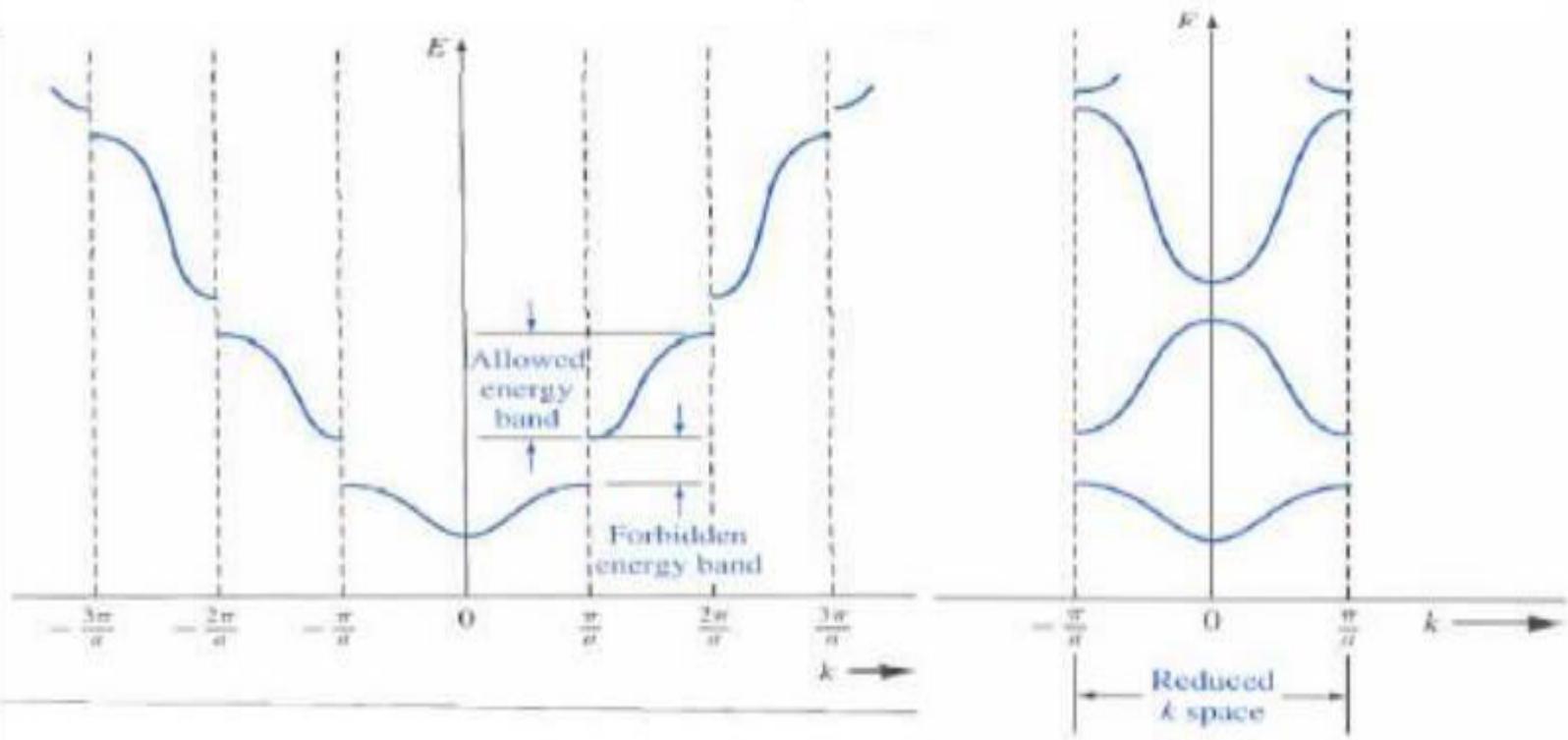
In this case, the Energy of an electron is Kinetic, shows it is a free electron.

This indicates the nature of a conductor.



# E-K Diagram

E-K Diagram in Kronig-Penney Model





## E-K Diagram Discussion

- All real K vectors lead to propagate electron states, results to allowed states.
- All imaginary K vectors cannot propagate electron states, results to forbidden states.
- If the potential barrier between the walls is strong, energy bands are narrow and wide apart.
- If the potential barrier is weak, energy bands are wide and closely packed.



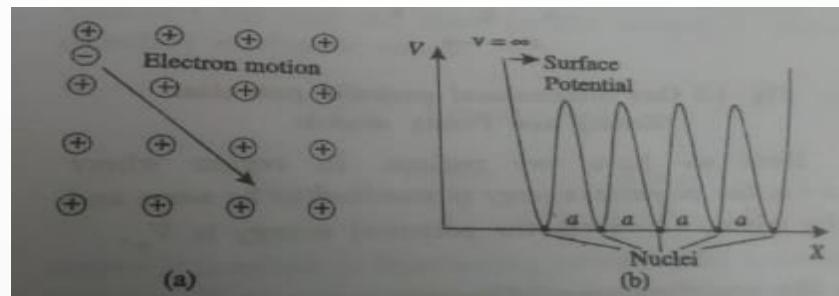
## Band Theory or Zone Theory

- The free electron theories failed to explain why some solids are conductors, insulators and semiconductors.
- A solution to this problem was given by band theory of solids.
- According to free electron theory, the potential energy of an electron inside the crystal is constant (zero). So it can move freely inside the crystal and is restrained only by the surface of the crystal.



## Postulates of Band Theory

- According to band theory, potential energy of an electron within the crystal is periodic due to periodicity of the crystal. i.e. free electrons move inside periodically in the lattice.
- The potential energy of the solid varies periodically with the periodicity of space lattice.
- It is assumed that the potential energy of the electron at the positive ion site is zero and is maximum when it is half way between the adjacent nuclei.





## Brillouin Zone

Brillouin zones are defined as the boundaries in a crystal lattice that are marked by the values of propagation wave vector in which the electrons can have allowed energy values without diffraction.

The relation between wave vector and the energy of an electron in a constant potential field is given by,  $E = n^2 h^2 / 8ma^2$

The wave vector  $K = n\pi / a$

From this,  $a = n\pi / K$

Substituting in E, we get  $E = K^2 h^2 / 8\pi^2 m$

○ Also,  $K = \pm \pi/a, \pm 2\pi/a, \pm 3\pi/a, \dots$

If we plot a graph between E and K, the curve obtained is in the form of parabola with discontinuities.

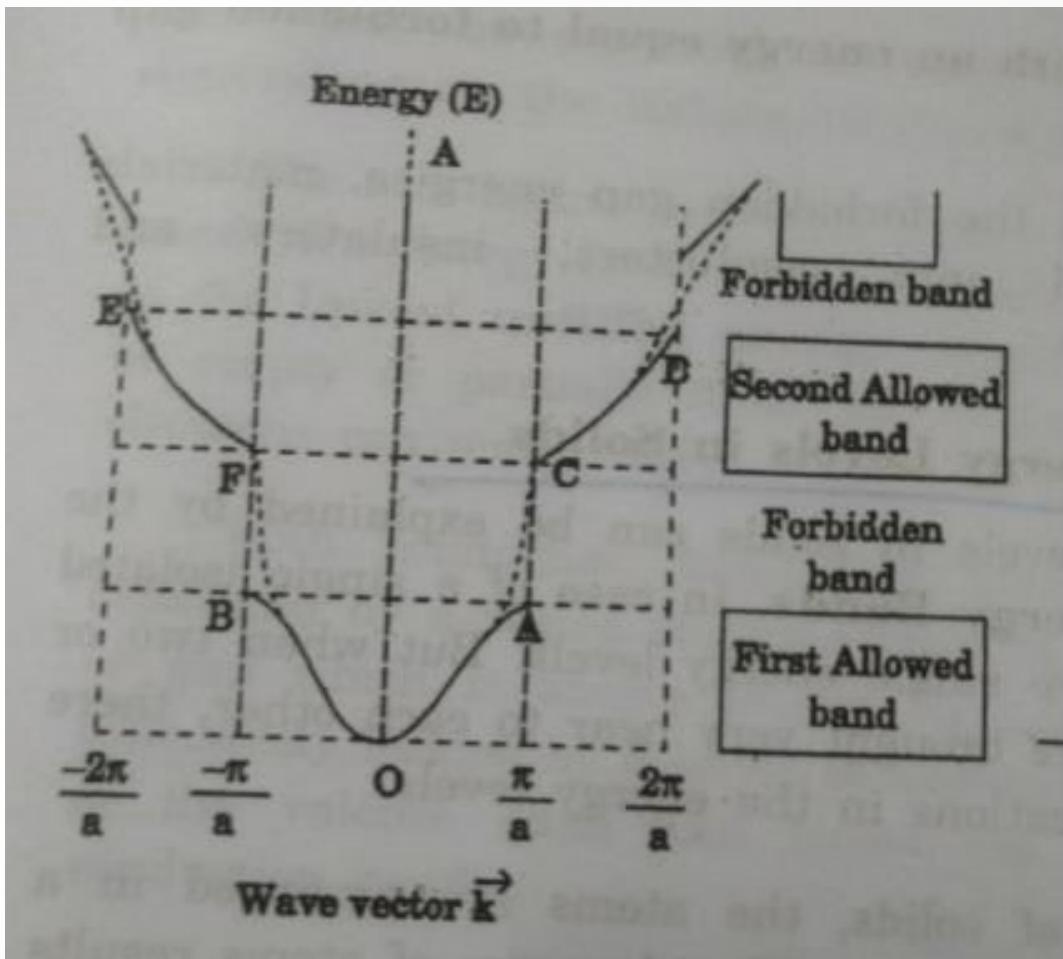


## Brillouin Zone

From the graph, it is seen that the energy of an electron increases continuously from 0 to  $\pm \pi/a$ , then the electron meets the wall and is reflected.

This range of allowed energy values in the region between  $-\pi/a$  to  $+\pi/a$  is

called **first Brillouin zone**





## Brillouin Zone

The second allowed energy value consists of two parts. One energy value from  $\pi/a$  to  $2\pi/a$  and another from  $-\pi/a$  to  $-2\pi/a$ , which is called **second Brillouin zone**.

Similarly, there will be 3<sup>rd</sup>, 4<sup>th</sup> etc. Brillouin zones for various ranges for different k values.

Also, each Brillouin zone is separated by break up energy values known as **forbidden zone or Energy gap**.

Thus, we conclude that the electrons can go from one Brillouin zone to the other only when it is supplied with an energy equal to forbidden gap energy.



## Origin of Energy Levels in Solids

Energy levels in solids can be explained by the concept Energy Bands.

In case of solids, the atoms are arranged in a systematic space lattice. The closeness of atoms results in the intermixing of electrons of neighboring atoms.

Due to this intermixing, the number of permissible energy levels increases, as a result the electrons are free to move in increased energy levels of the atoms which in turn increases the conduction of the solids.

A set of closely spaced energy levels is called an energy band.



## Origin of Energy Levels in Solids

Valence Band: The electrons in the outermost shell are called valence electrons. The band formed by a series energy level containing the valence electrons is known as **Valence band**. Thus, it is defined as a band which is occupied by the **valence electrons**. The valence band may be **partially or completely filled** up depending on the nature of the material.

Conduction Band: The next higher permitted band is the conduction band.

The conduction band energy levels are defined as the **lowest unfilled energy band**. This band may be **empty or partially filled**. Here the electrons can move freely.

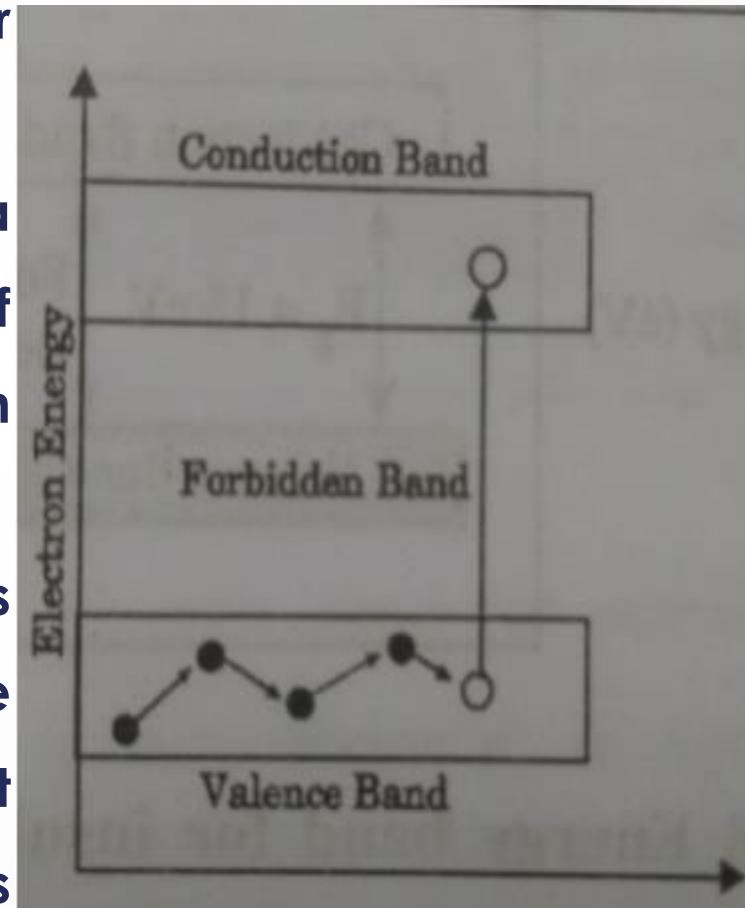


# Origin of Energy Levels in Solids

The conduction band and valence band are separated by a region or gap known as **forbidden band**.

This band is collectively formed by a series of energy levels above the top of valence band and below the bottom of conduction band.

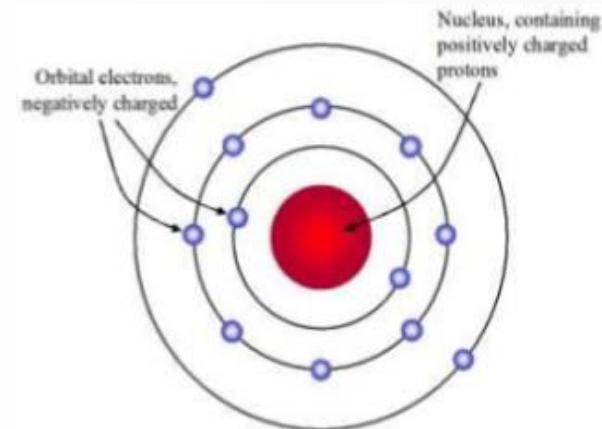
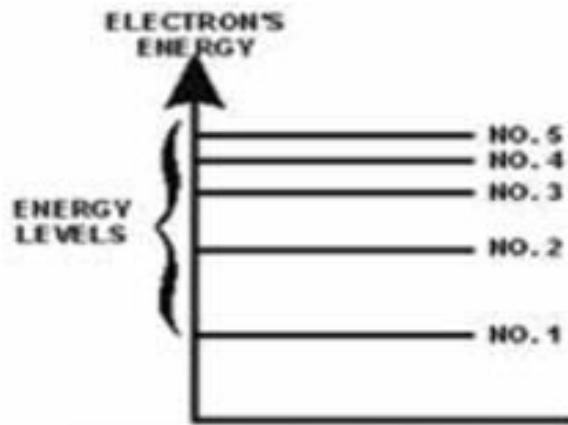
Hence, no electron can exist in this band. When an electron in the valence band absorbs enough energy, it crosses the forbidden gap and enters into the conduction band.





## ENERGY BANDS IN SOLIDS

There are discrete energy levels in case of an isolated atom.



The following are the important energy band in solids:

- Valence band
- Conduction band
- Forbidden energy gap or Forbidden band



## ENERGY BANDS IN SOLIDS

### ❖ Valance band

The band of energy occupied by the valance electrons is called **valence band**. The electrons in the outermost orbit of an atom are known as **valance electrons**. This band may be **completely or partial filled**.

Electron can be move from one valance band to the conduction band by the application of external energy.



## ENERGY BANDS IN SOLIDS

### ❖ Conduction band

The band of energy occupied by the conduction electrons is called **conduction band**. This is the uppermost band and all electrons in the conduction band are free electrons.

The conduction band is empty for insulator and partially filled for conductors.



## ENERGY BANDS IN SOLIDS

### ❖ **Forbidden Energy Gap or Forbidden band**

The gap between the valance band and conduction band on energy level diagram known as **forbidden band or energy gap**.

Electron are never found in the gap. Electrons may jump from back and forth from the bottom of valance band to the top of the conduction band. But they never come to rest in the forbidden band.



## Properties of Conductors

- It is a material that easily conducts electrical current
- Most metals are good conductors
- It may have one valence electron very loosely bound to the atom
- These loosely bound valence electrons can become free electrons with the addition of a small amount of energy
- The free electrons are responsible to carry current
- Free electrons are the charge carriers in a conductor
- Examples: Copper (Cu), Silver (Ag), Gold (Au), Aluminum (Al) etc.



# Properties of Insulators

- It does not conduct electrical current under normal conditions
- Good insulators are compounds rather than single-element materials
- It have very high resistivity's
- The atoms are tightly bound to one another so electrons are difficult to strip away for current flow
- Valence electrons are tightly bound to the atoms
- Few free electrons are present in an insulator.
- Examples : Rubber, plastics, glass, mica, quartz etc.



# Properties of Semiconductors

- It is a material between conductors and insulators
- Semiconductor in its pure state is neither a good conductor nor a good insulator i.e. At 0K, it acts as an insulator and if temperature is given or impurities are added it acts as a conductor
- Free electrons and holes are the charge carriers
- Single-element semiconductors are antimony, arsenic, Boron, Polonium, Tellurium, Silicon, Germanium.
- Compound semiconductors are Gallium arsenide, Indium phosphide, Gallium nitride, silicon carbide etc.



# Basic Definitions

## Lattice:

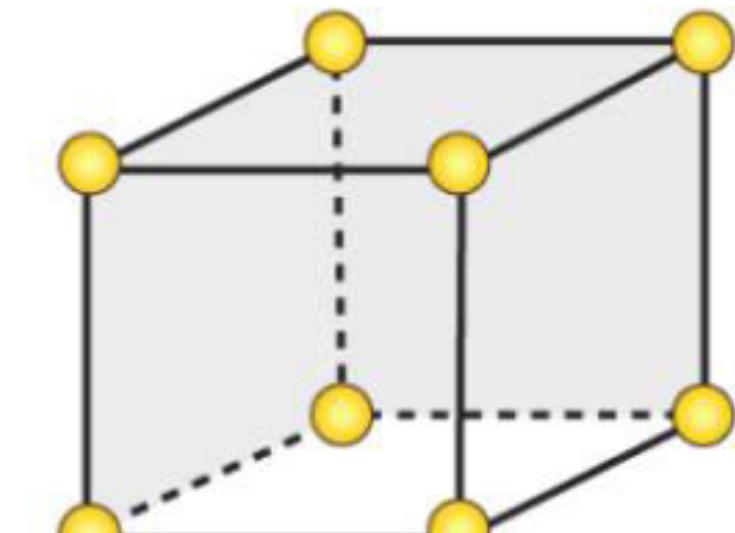
An array of imaginary points representing the position of atoms in a crystal.

## Unit Cell:

- The smallest repeating unit of the crystal lattice is a unit cell.
- It is the building blocks of a crystal.

## Primitive cell:

It is the simplest type of unit cell that contains only one lattice point per unit cell.





## Brillouin Zone

The Brillouin zones are used to describe and analyze the electron energy in the band energy structure of crystals.

The different Brillouin zones correspond to primitive cells of a different type that come up in the theory of electronic levels in a periodic potential. The first Brillouin zone is considered as the Wigner-Seitz (WS) primitive cell in the reciprocal lattice. In other words, the first Brillouin zone is a geometrical construction to the WS primitive cell in the k-space.



## Brillouin Zone

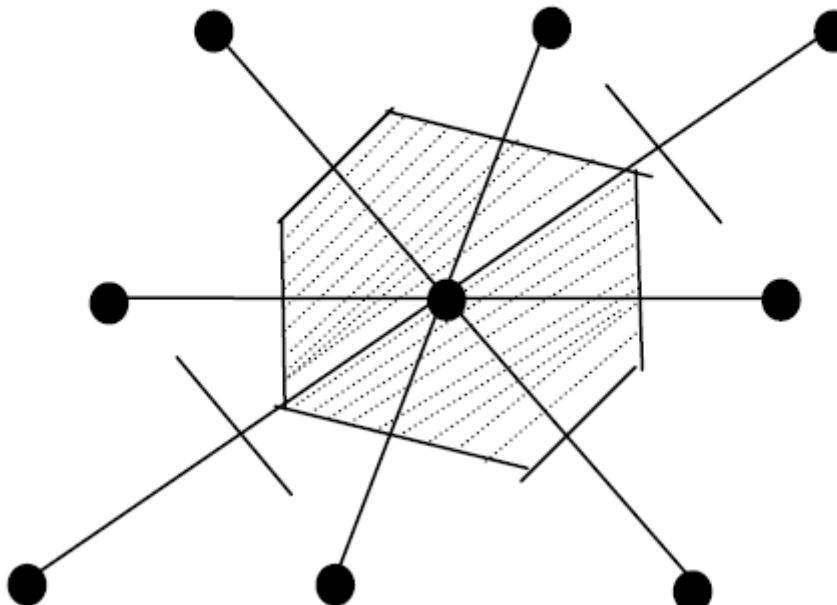
*The procedure of constructing Weigner Seitz primitive cell in a direct lattice:*

- Consider a two dimensional square lattice.
- Draw lines to connect a given lattice point to all nearby lattice points.
- Draw perpendicular bisectors to the line joining the points to its nearest neighboring points.
- The innermost region bounded by the perpendicular bisectors is identified as the weigner Seitz primitive cell.

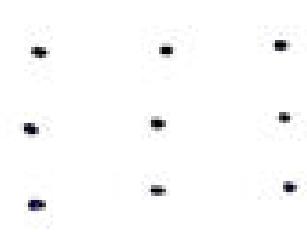


# Brillouin Zone

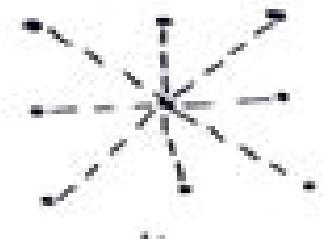
**Construction of WS primitive cell in a 2D lattice**



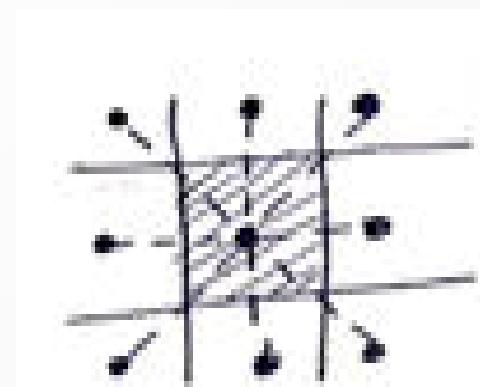
**STEP : 1**



**STEP : 2**



**STEP : 3**



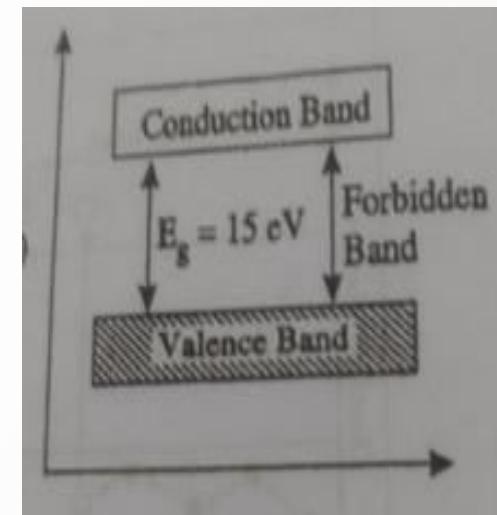


# Classification of Electronic Materials

Based on the magnitude of forbidden gap, the solids are classified into insulators, semiconductors and conductors.

## Insulators:

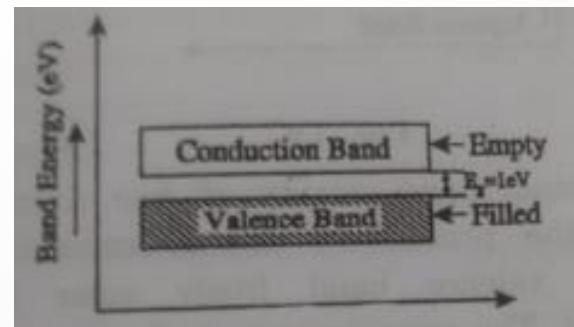
- At 0K, the valence band is completely filled and conduction band is empty.
- The forbidden energy band is very wide.
- The electrons cannot jump from valence band to conduction band because the valence electrons are very tightly bounded to the atoms.
- Even in the presence of electric field, the electrons cannot jump from valence band to conduction band.





## Semiconductors

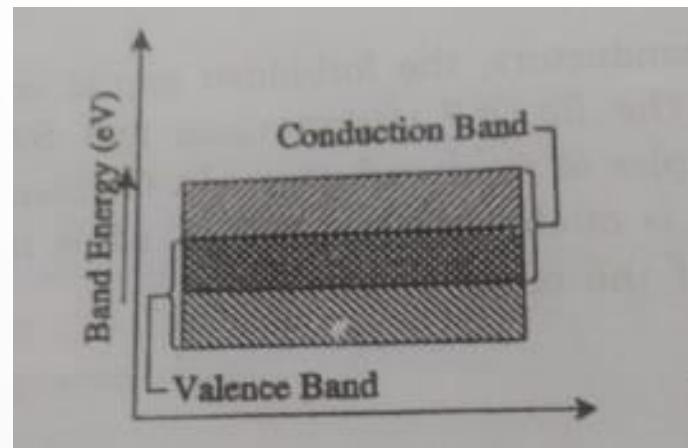
- The forbidden gap is very small. For Germanium it is 0.7 eV & for Silicon it is 1.1 eV.
- The electrical properties of semiconductors lies between conductors and insulators.
- At 0K, there are no free electrons in conduction band but valence band is completely filled.
- When a small amount of energy is supplied, the electrons can easily jump from valence band to conduction band , since the forbidden gap is very small.





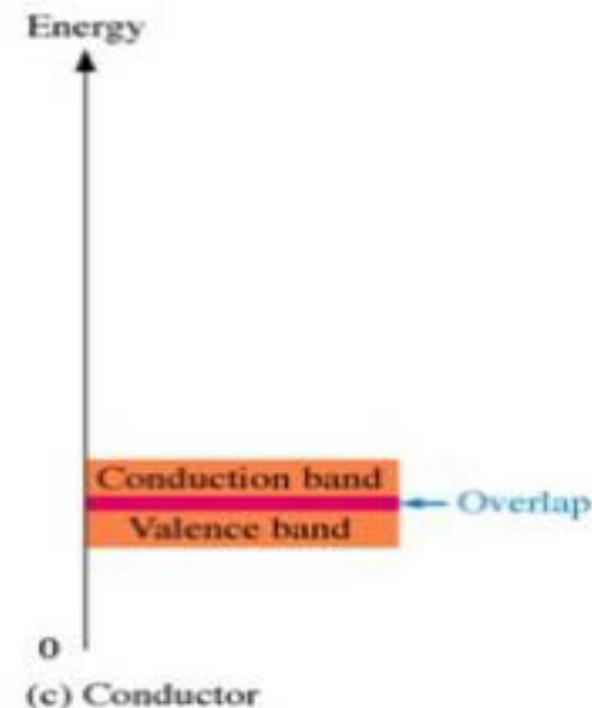
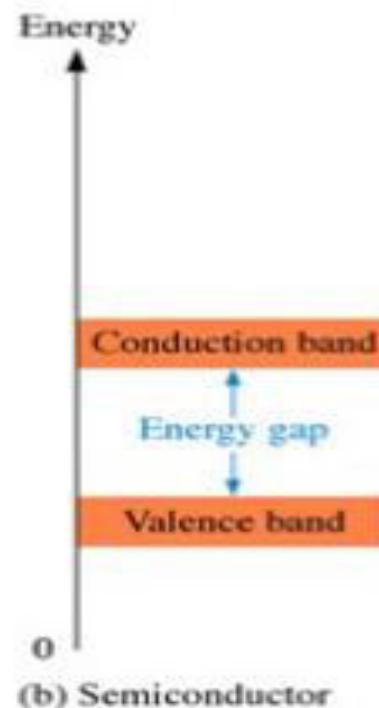
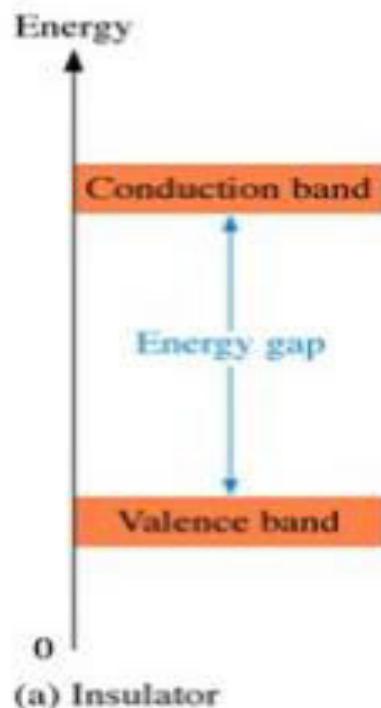
## Conductors

- In conductors, there is no forbidden gap, because the valence band and conduction bands overlap each other.
- In the conduction band, plenty of free electrons are present for electrical conduction.
- The electrons from valence band freely enter into the conduction band.
- The total current in conductors is only due to the flow of electrons.





# Energy Bands for, Insulator, Semiconductor and Conductor





# Energy band structure in semiconductors

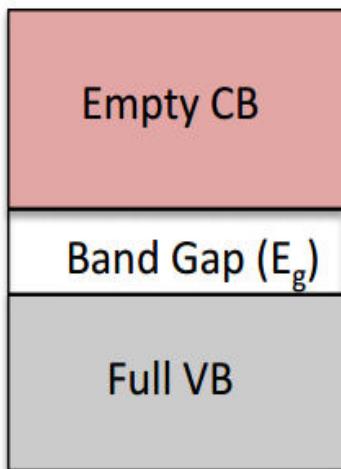
**In a semiconductors, At 0K,**

- The lower energy bands are completely filled.
- The higher energy bands are completely empty.
- The nearly upper filled band is called the valence band.
- The nearly lowest empty band is called the conduction band.
- The gap between valence band and conduction band is called the band gap.
- The totally filled band and unfilled band do not conduct current.
- The uppermost filled and lowermost unfilled only conduct current in a semiconductor.

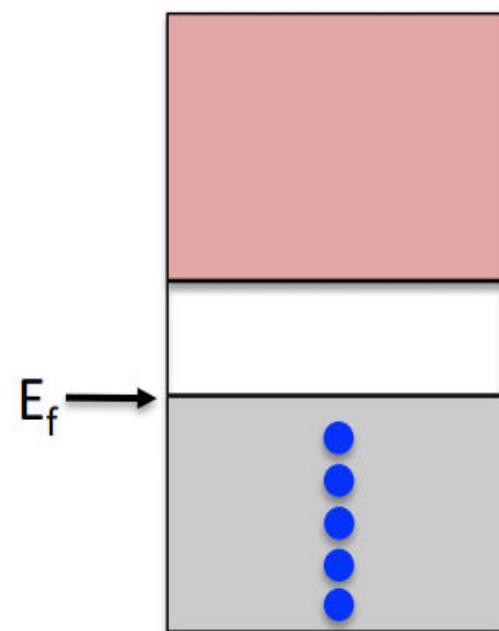


# Energy band structure in semiconductors

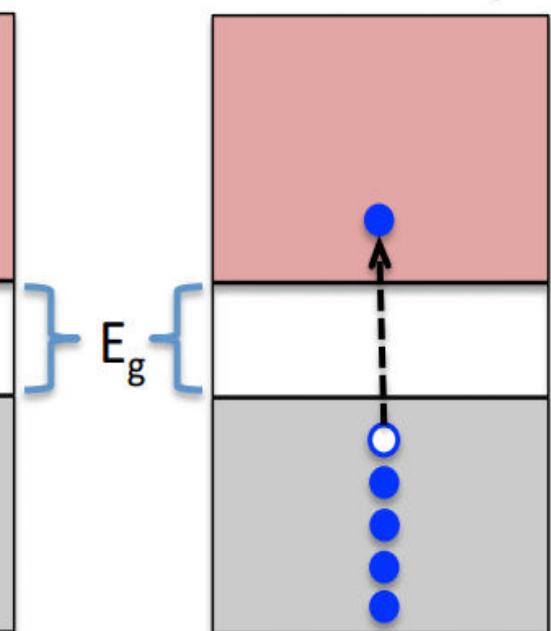
Energy Band  
Diagram at 0K



0 Kelvin



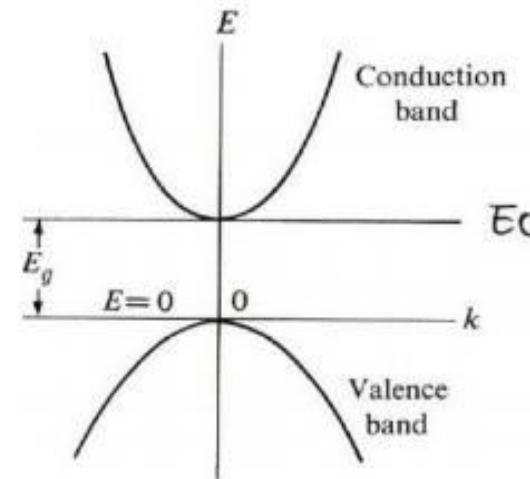
Room Temp





# Band Gaps in Semiconductors

Energy Band Diagram at 0K

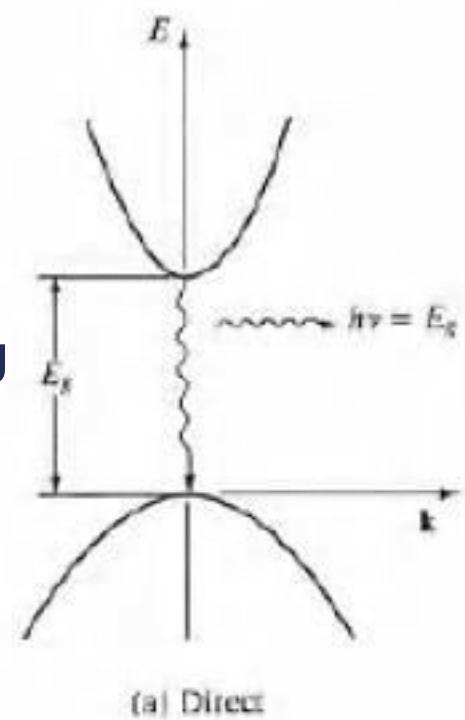


- Based on the Band gap, semiconductors are classified into
- **Direct band gap semiconductors**
  - **Indirect band gap semiconductors**



# Direct Band Gap Semiconductors

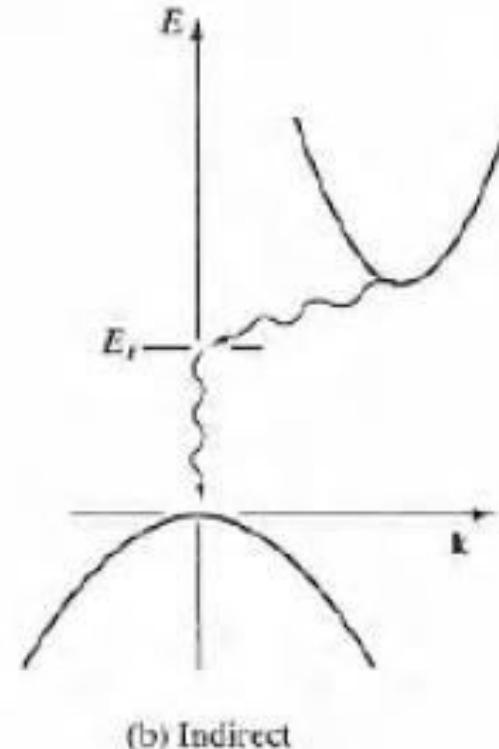
- The conduction band minima and the valence band maxima occurs at the same value of momentum.
- An electron from the conduction band returns to the valence band without changing its momentum and releases energy in the form of light (photons).
- These direct band gap materials are the efficient sources of light such as LEDs, Lasers etc.





# Indirect Band Gap Semiconductors

- The conduction band minima and valence band maxima occurs at different momentum.
- The electrons from the conduction band returns to the valence band with varying momentum and releases energy in the form of heat (phonons).
- These indirect band gap materials are more efficient for making diodes, transistors etc.
- Example: Silicon, Germanium.





## Importance of Direct & Indirect Band Gap Semiconductors

The difference between direct and indirect band structure is very important for deciding which semiconductors can be used in devices requiring light output.



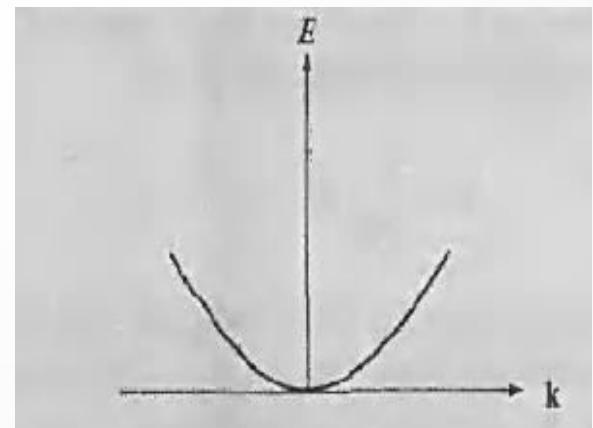
## Effective Mass in Semiconductors

The E-K relationship for the free electron is calculated and is related to the electron mass.

The electron momentum is  $p = mv = \hbar k$ . Then

$$E = \frac{1}{2}mv^2 = \frac{1}{2}\frac{p^2}{m} = \frac{\hbar^2}{2m}k^2$$

Thus the electron energy is parabolic with wave vector K.





## Effective Mass in Semiconductors

When an electron is moving inside the solid material the potential field will affect the movement of electron. For low kinetic energy,

$$E = P / 2m^*$$

Where  $P$  is the crystal momentum.

i.e. a conduction electron behaves as a particle with an effective mass  $m^*$ .

The effective mass of an electron ( $m^*$ ) in a band is given as

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

- $m^*$  reflects the periodic potential and the motion of an electron.
- $m^*$  is inversely proportional to the second derivative of E – K diagram.



## Effective Mass in Semiconductors

For a free electron if  $m^* = m$ , the conduction band energy of an electron in K-space is given as,

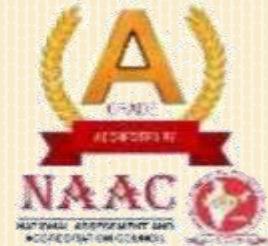
$$E = \frac{\hbar^2}{2m^*}k^2 + E_c$$

If this is compared with  $m^*$ , it shows that the effective mass is constant in the parabolic band.

Hence the conduction band effective mass is directly related to the band gap energy. i.e. if the band gap is small then the effective mass is also small. Hence the effective mass of an electron differs from band to band and also depends on the nature of the bond.



**Bharath**  
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(Declared as Deemed - to - be - University under section 3 of UGC Act 1956)



## UNIT - II

# SEMICONDUCTOR PHYSICS



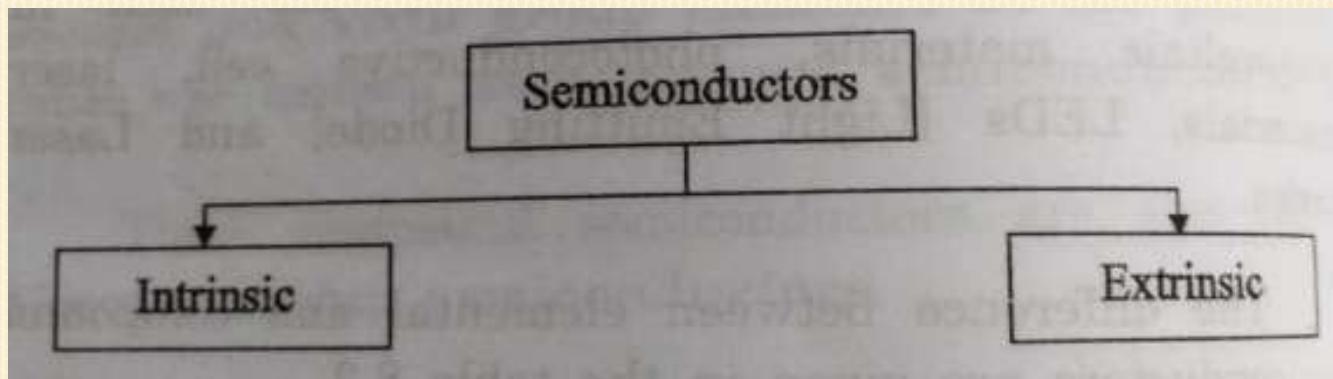
**PRESENTED BY**

**DR. C. RATHIKA THAYA KUMARI,**  
**Associate Professor,**  
**Department of Physics**

# Types of Semiconductors

When a suitable impurity is added to a pure semiconductor, its electrical conductivity changes. Based on this property, Semiconductors are classified into,

- Intrinsic Semiconductor or Pure Semiconductor
- Extrinsic Semiconductor or impure Semiconductor



# Intrinsic Semiconductor

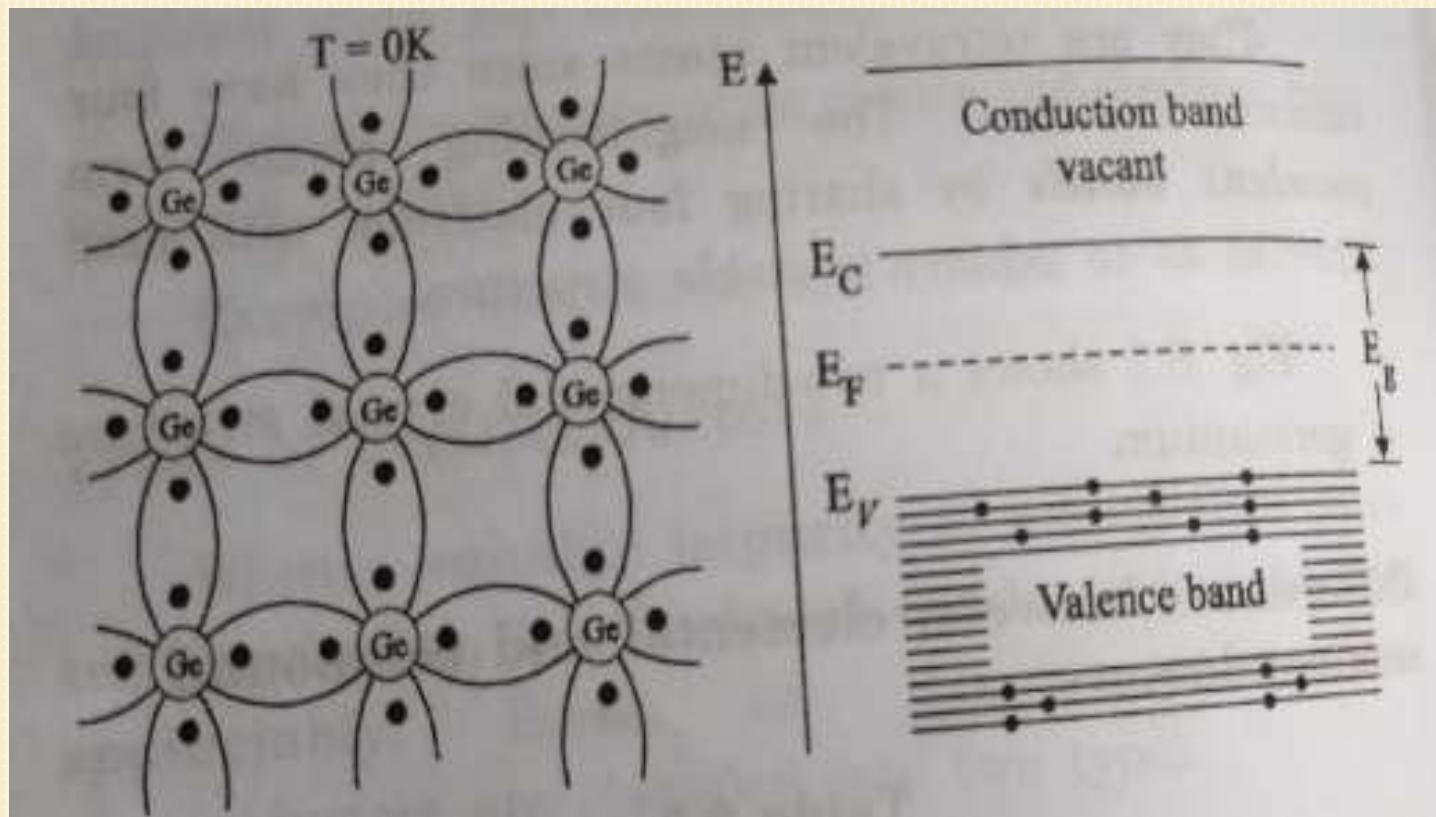
A semiconductor in extremely pure form without the addition of impurities is known as an intrinsic semiconductor. Its electrical conductivity can be changed due to thermal excitation.

**Examples:** Germanium, Silicon

- They belong to IV<sup>th</sup> group of the periodic table.
- Germanium has 32 electrons and Silicon has 14 electrons in their atomic structures.
- They are tetravalent atoms since they have four valence electrons.
- The neighboring atoms form covalent bonds by sharing four electrons with each other so as to achieve stable structure.

# Intrinsic Semiconductor

- At very low temperature 0K, no free electrons are available for conduction.
- Semiconductor behaves as an insulator at very low temperature

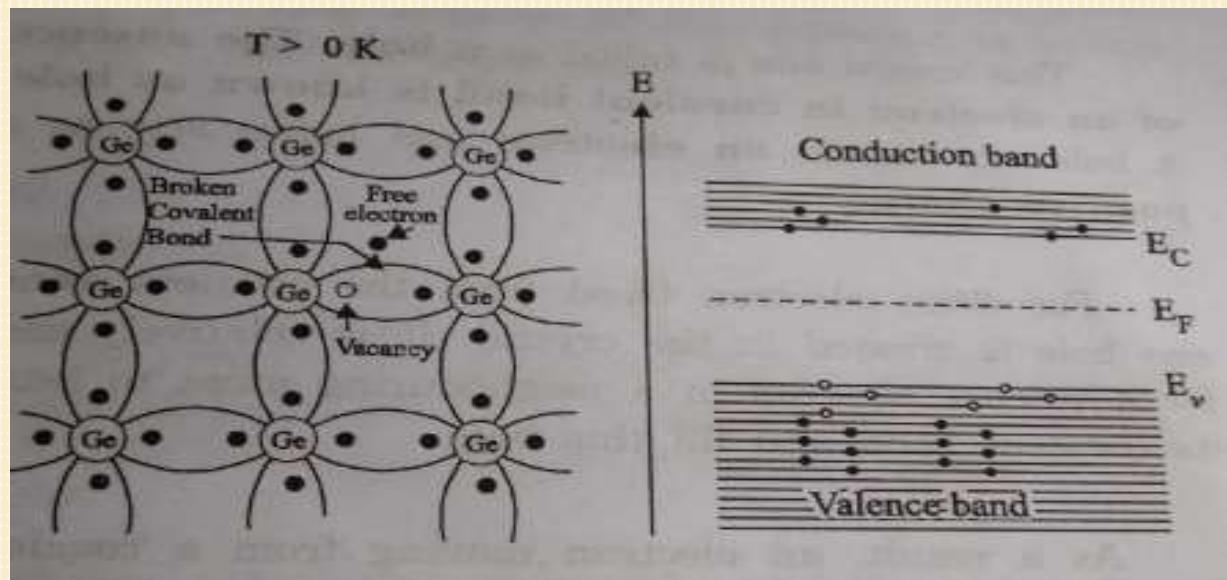


# Charge Carriers - Intrinsic Semiconductor

- To get free electrons, the covalent bonds must be broken.
- When the temperature is increased, some of the electrons acquire sufficient energy to break the covalent bonds.
- Once the electrons are liberated from the bond, they become free electrons.
- Such free electrons move randomly through the crystal.
- When an electric field is applied, free electrons acquire directional motion and contribute electrical conductivity.
- The energy required to break a covalent bond and to set an electron free is equal to the band gap energy .
- It is 0.72 eV for germanium and 1.1 eV for Silicon.

# Charge Carriers - Intrinsic Semiconductor

- When an electron acquires energy  $E_g$  it jumps from valence band to conduction band. As a result, a **vacant site** is created in valence band. This vacant site is called as a **hole**.
- The absence of an electron in covalent bond is known as hole.
- A hole can attract an electron and act as a positive charge.

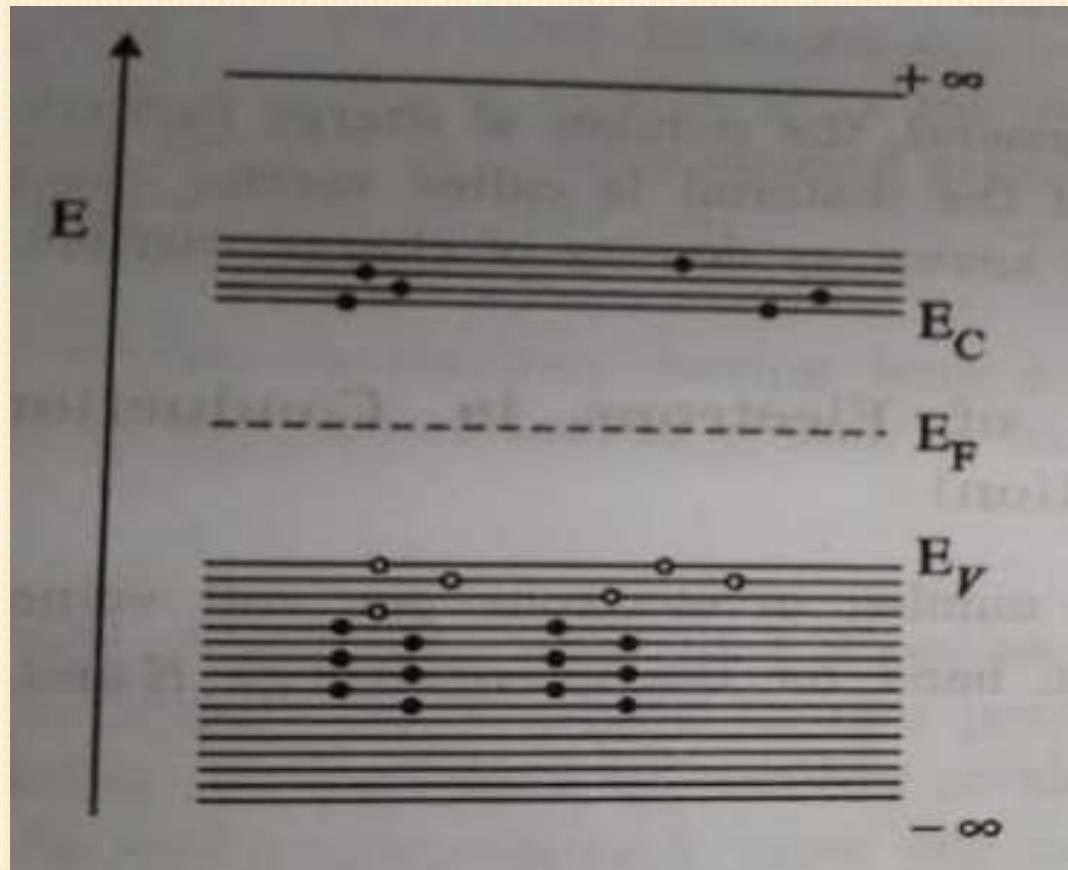


## Charge Carriers - Intrinsic Semiconductor

- For every electron freed from the covalent bond, one hole is created. As a result, an electron moving from a covalent bond to fill a hole leaves behind a hole in its original position.
- The hole effectively moves in a direction opposite to the electron.
- The hole in its new position may now be filled by an electron from another covalent bond and move one step in the direction opposite to the motion of the electron.
- Hence, in an intrinsic semiconductor, the current conduction is due to the movement of electrons and holes.
- Therefore, Number of electrons is equal to the Number of holes at any temperature.

# Carrier Concentration in an Intrinsic Semiconductor

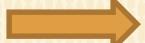
The number of charge carriers per unit volume of the material is called Carrier concentration (density of charge carriers).



Energy Band Diagram  
for intrinsic  
semiconductor

# Carrier Concentration in an Intrinsic Semiconductor

Number of electrons in the conduction band (n) is



$$n = 2 \left( \frac{2 \pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_C) / kT}$$

$$p = 2 \left( \frac{2 \pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F) / kT}$$



Number of holes in the valence band (p) is

In an intrinsic semiconductor, Number of electrons in the conduction band is equal to the Number of holes in the valence band. i.e.  $n = p = n_i$

where  $n_i$  is the intrinsic carrier concentration.

$$np = n_i * n_i = n_i^2$$

# Carrier Concentration in an Intrinsic Semiconductor

Substituting the expressions for n & p we get,

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

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

$$n_i^2 = 4 \left( \frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} e^{-E_g/kT}$$

... (1)

where  $E_c - E_v = E_g$  is the forbidden energy gap.

$$n_i = 2 \left( \frac{2\pi kT}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2kT}$$

# Variation of Fermi energy level with Temperature in an Intrinsic Semiconductor

For an intrinsic semiconductor, number of electrons will be same as that of number of holes.  $n_e = n_h$

Equating the values of  $n_e$  and  $n_h$  we get,

$$\left( m_e^* \right)^{3/2} e^{(E_F - E_c)/K_B T} = \left( m_h^* \right)^{3/2} e^{(E_v - E_F)/K_B T}$$

$$\left\{ \frac{m_h^*}{m_e^*} \right\}^{3/2} = \frac{e^{(E_F - E_c)/K_B T}}{e^{(E_v - E_F)/K_B T}}$$

$$= e^{(E_F - E_c - E_v + E_F)/K_B T}$$

# Variation of Fermi energy level with Temperature in an Intrinsic Semiconductor

$$\left( \frac{m_h^*}{m_e^*} \right)^{3/2} = e^{(2E_F - (E_v + E_c)) / K_B T}$$

Taking log on both sides,

$$3/2 \log \left( \frac{m_h^*}{m_e^*} \right) = \frac{[2E_F - (E_v + E_c)]}{K_B T}$$

$$2E_F = E_c + E_v + \frac{3}{2} K_B T \log \frac{m_h^*}{m_e^*}$$

$$E_F = \frac{E_c + E_v}{2} + \frac{3}{4} K_B T \log \left( \frac{m_h^*}{m_e^*} \right)$$

# Variation of Fermi energy level with Temperature in an Intrinsic Semiconductor

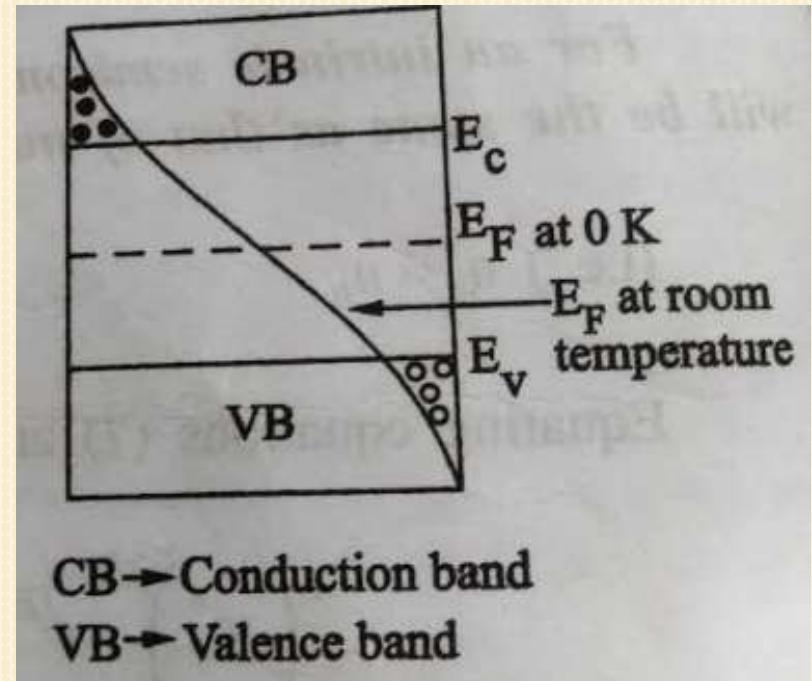
If  $m_h^* = m_e^*$ , then  $\log \frac{m_h^*}{m_e^*} = 0$  [ $\because \log 1 = 0$ ]

Fermi Energy of an intrinsic semiconductor is

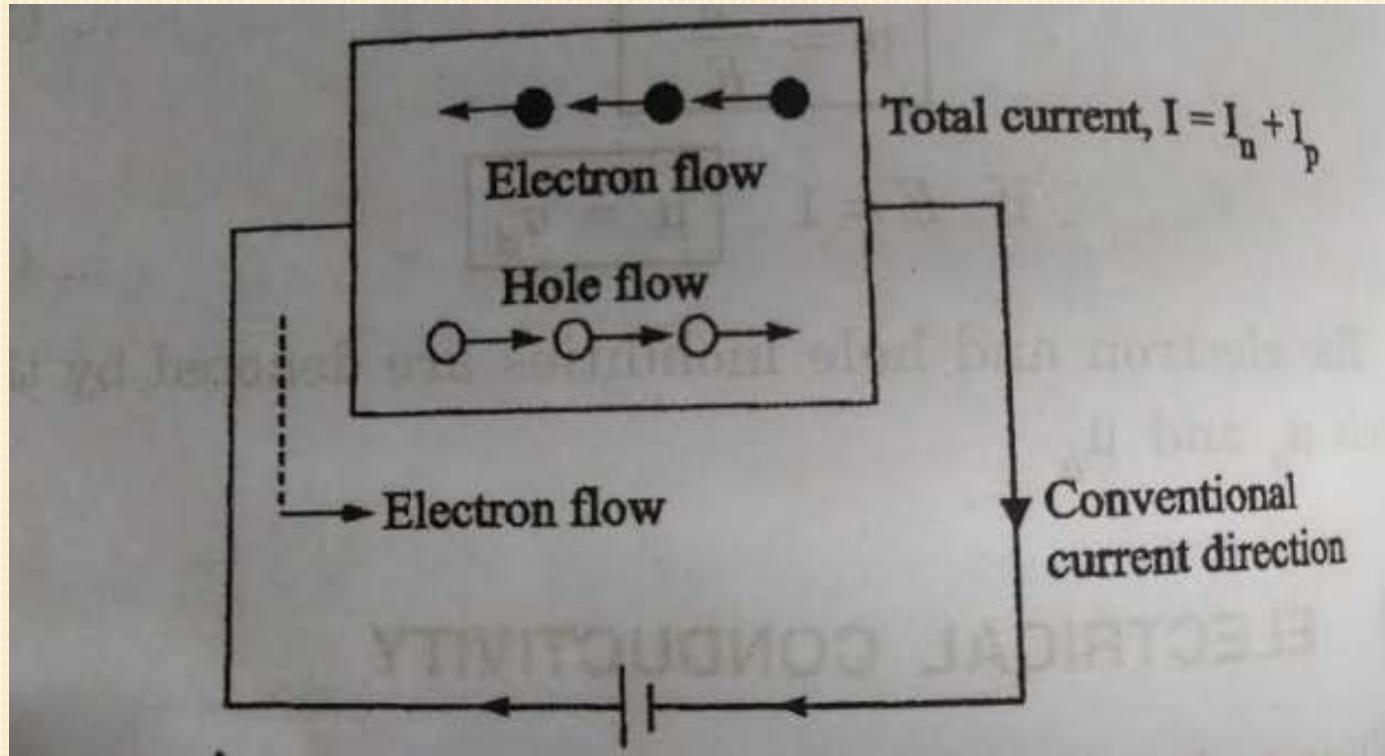


$$E_F = \frac{E_c + E_v}{2}$$

- The Fermi level lies in the midway between Ec and Ev at T= 0K.
- Also in case  $m_h^* > m_e^*$  and the Fermi energy level slightly increases with the increase in temperature.



# Conduction of electrical current in an Intrinsic Semiconductor



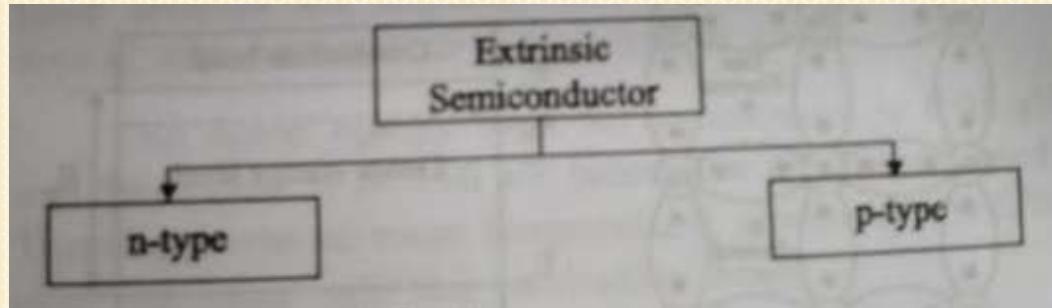
The charge carriers in a semiconductor are electrons and holes. Both the charge carriers will take part in the current conduction

# Extrinsic Semiconductor

- In a pure semiconducting material, if the charge carriers originate from impurity atoms added to a original material, then this type of semiconductor is called **extrinsic semiconductor**.
- This can be obtained by doping trivalent or pentavalent impurities in a tetravalent semiconductor.
- The electrical properties can be changed easily even with the addition of very little amount of impurities.
- The method of adding impurities to a pure semiconductor is known as **doping**. The added impurities are called **dopants**.
- The addition of impurities will increase the number of electrons and holes, which increases electrical conductivity.

# Extrinsic Semiconductor

Based on the impurity added, Semiconductors are classified into two types:



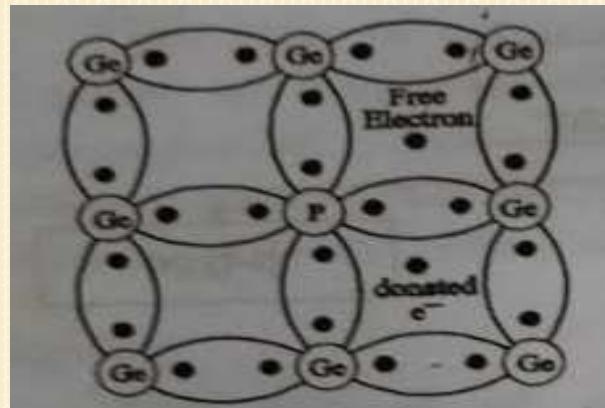
## n - type Semiconductor

When a small amount of pentavalent impurity is added to a pure semiconductor, it becomes a **n-type semiconductor**.

Examples of pentavalent impurities are **Arsenic, Antimony**.

## n type semiconductor

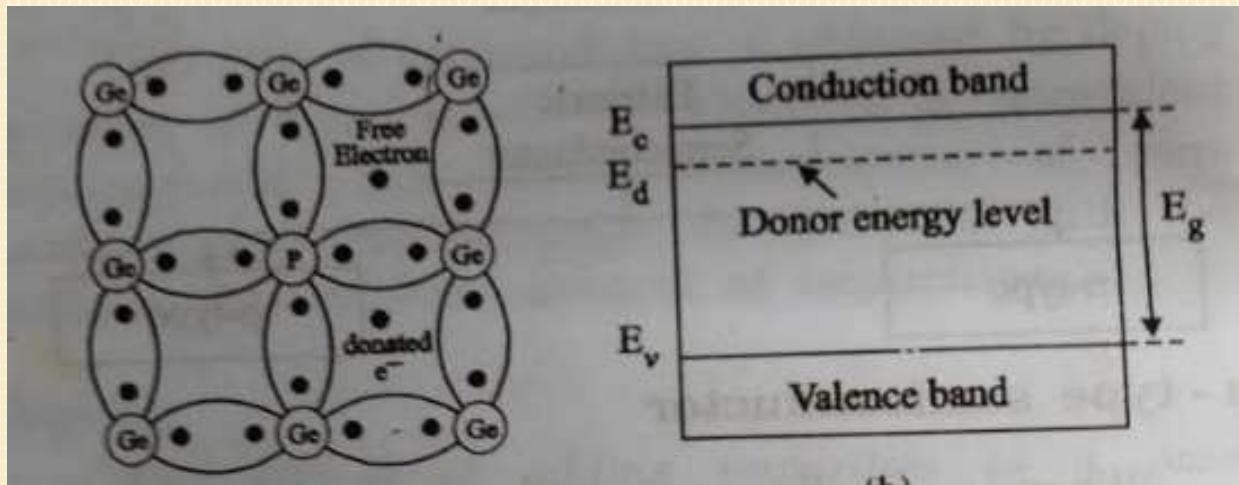
- A pentavalent impurity having five valence electrons is added to a pure semiconductor having four valence electrons.
- These four electrons of germanium form a covalent bond with four valence electrons of phosphorus. The fifth electron which is free finds no other electron to form covalent bond.
- This fifth electron acts as a conduction electron
- A very small amount of energy is needed to separate the fifth electron.



## n - type semiconductor

- The addition of pentavalent impurity gives a large number of free electrons in the n-type semiconductor.
- Thus, the number of free electrons is more than the number of holes in n-type semiconductor. So in this case, electrons are the majority charge carriers and holes are the minority charge carriers.

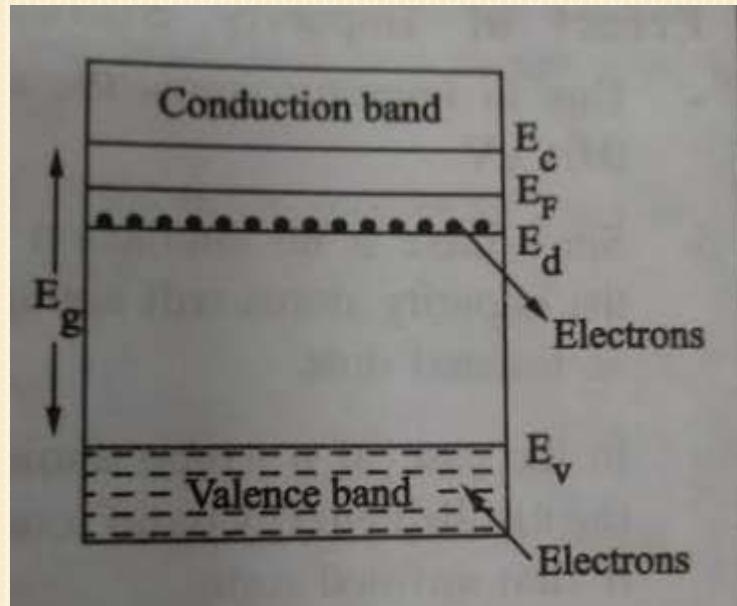
## Energy band diagram for n - type semiconductor



## Energy band diagram for n - type semiconductor

- The excess free electrons will occupy in a separate energy level which is just below the conduction band. Such energy levels are called donor energy levels and the corresponding atoms in the donor energy levels are called donor atoms.
- This donor atoms are discrete and do not form a band because the donor atoms are far away in the crystal and hence their interaction is small.
- The donor energy level for germanium is 0.01 eV and for silicon is 0.05 eV below the conduction band.
- Hence, even at room temperature almost all the donor electrons enter into the conduction band.

# n - type semiconductor



$E_c$  – Conduction band Energy level

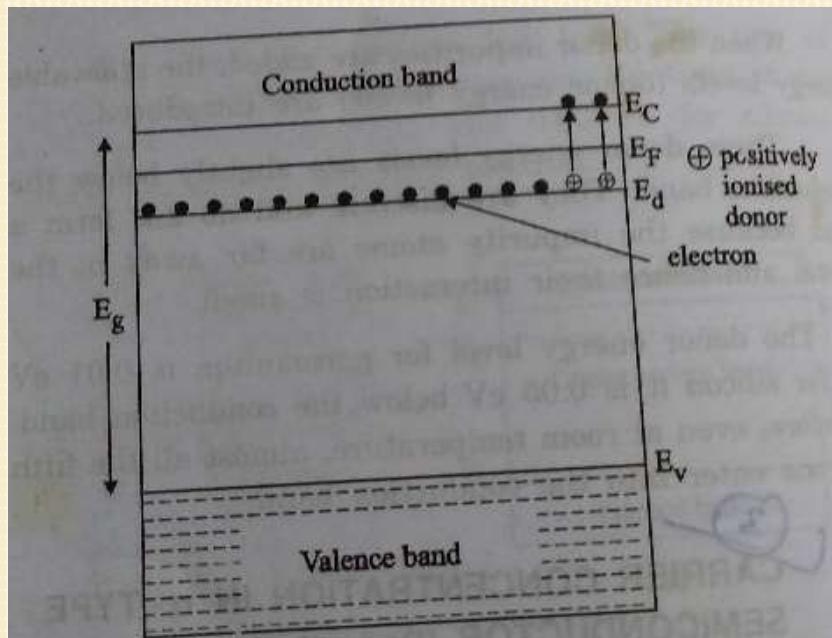
$E_v$  – Valence band Energy level

$E_d$  – Donor energy level

When a pentavalent impurity is added to a pure semiconductor, four electrons form a covalent bond with a neighboring atoms and excess free electron will occupy in an energy level close to the conduction band. Such energy levels are called **donor energy levels**.

# Carrier concentration in n - type semiconductor

In the n-type semiconductor, the donor level is just below the conduction band.



$N_d$  – donor concentration

$E_d$  - Energy of the donor level

$E_c$  – Conduction band energy level

Density of electrons in the conduction band is



$$n = 2 \left( \frac{2 \pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_C)/kT}$$

$$\text{Density of ionised donors} = N_d [1 - F(E_d)]$$

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

## Carrier concentration in n - type semiconductor

By Simplifying,

The density of ionised donors is

$$\frac{N_d}{1 + e^{(E_F - E_d)/kT}}$$

The carrier concentration in an n-type semiconductor is given as,

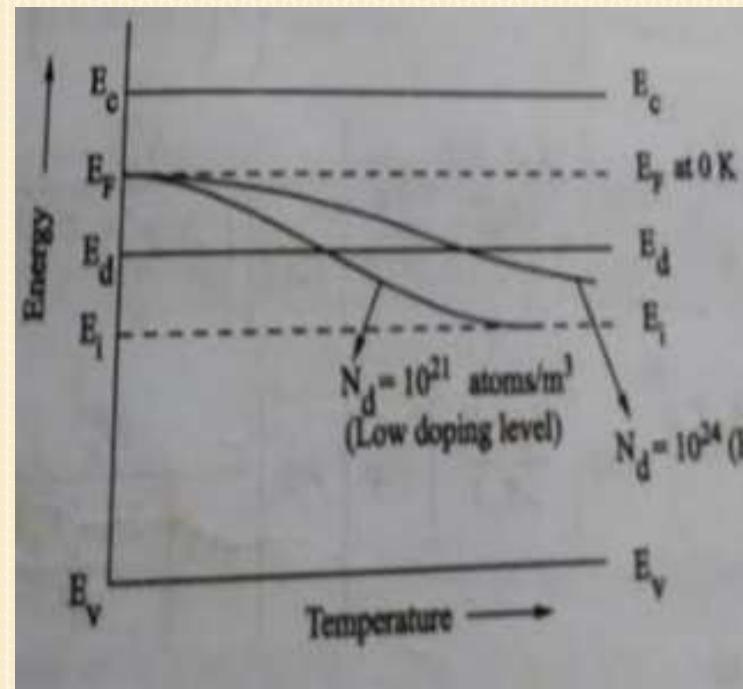
$$n = (2N_d)^{1/2} \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/4} e^{-\Delta E / 2kT}$$

Where  $\Delta E = E_c - E_d$  is the ionisation energy of the donor.

i.e.  $\Delta E$  denotes the amount of energy required to transfer an electron from the donor energy level  $E_d$  to the conduction band  $E_c$

# Variation of Fermi Energy level with Temperature and Impurity concentration in n - type semiconductor

When the temperature is increased some electrons in  $E_d$  level may be shifted to conduction band and hence some vacant sites will be created in  $E_d$  levels. Hence the Fermi level shifts down to separate that empty levels and the filled valence band level for the doping level.

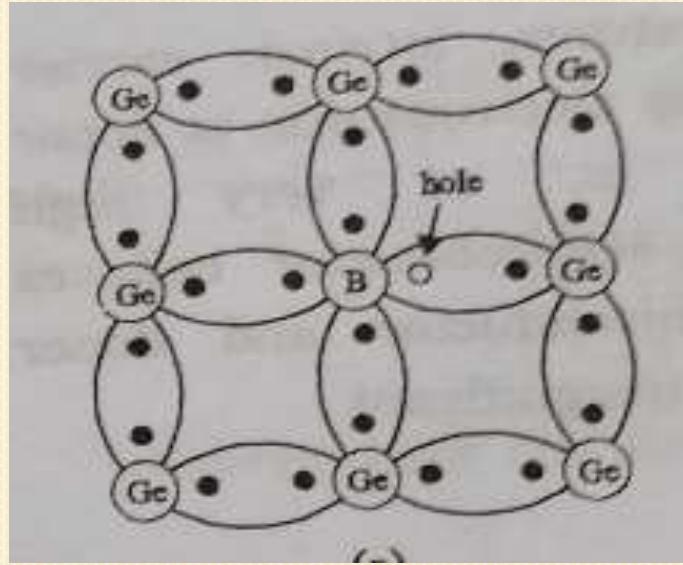


For the same temperature, if the impurity atoms are doped, then the electron concentration increases also the Fermi level increases.

## p type semiconductor

When a small amount of trivalent impurity is added to a pure semiconductor, it becomes a **p-type semiconductor**.

Examples of trivalent impurities are **Boron, Gallium, Indium**.



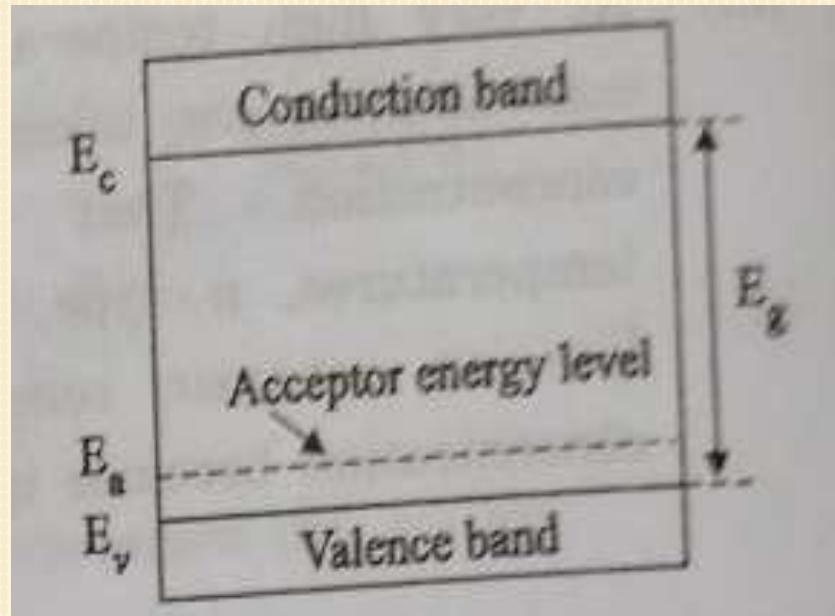
## p type semiconductor

- A trivalent impurity having three valence electrons is added to a pure semiconductor having four valence electrons.
- The three electrons of germanium form a covalent bond with three valence electrons of boron. One hole is created from each impurity atom.
- The addition of trivalent impurity gives a large number of holes in the p-type semiconductor.
- Thus, the number of holes is more than the number of electrons in p-type semiconductor. So in this case, holes are the majority charge carriers and electrons are the minority charge carriers.

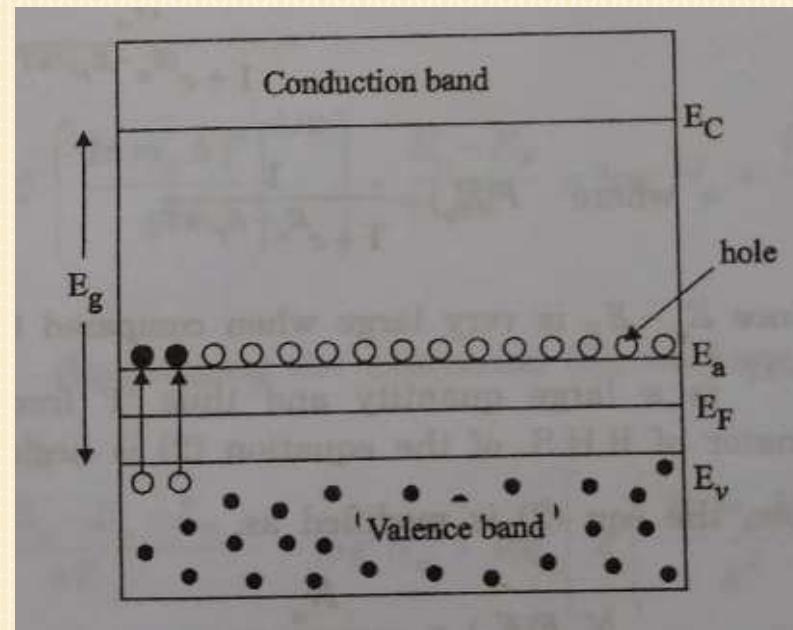
## Energy band diagram for p - type semiconductor

The excess holes will occupy in a separate energy level which is just above the valence band.

Such energy levels are called acceptor energy levels and the corresponding atoms in the acceptor energy levels are called acceptor atoms.



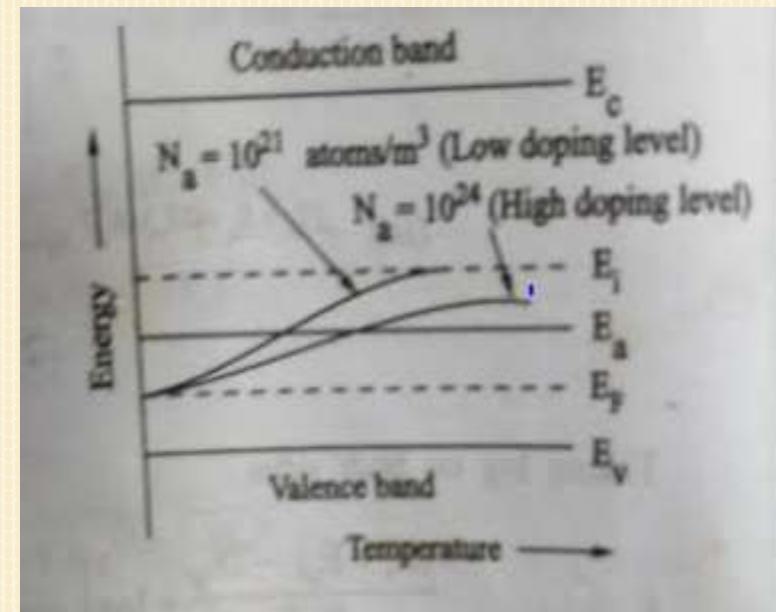
# Carrier Concentration in a p - type semiconductor



$$n_h = (2N_a)^{1/2} \cdot \left[ \frac{2\pi m_h^* K_B T}{h^2} \right]^{3/4} \cdot e^{(E_v - E_a)/2K_B T}$$

# Variation of Fermi Energy level with Temperature and Impurity concentration in p - type semiconductor

When the temperature is increased some electrons in the valence band will go to the  $E_a$  level by breaking the covalent bonds. Hence the Fermi level is shifted in the upward direction.



For the same temperature, if the impurity atoms are doped, then the hole concentration increases also the Fermi level decreases.

At low temperature, the Fermi level may be increased up to the level of intrinsic energy level  $E_i$ .

# SEMICONDUCTOR PHYSICS – U20PYBJ03

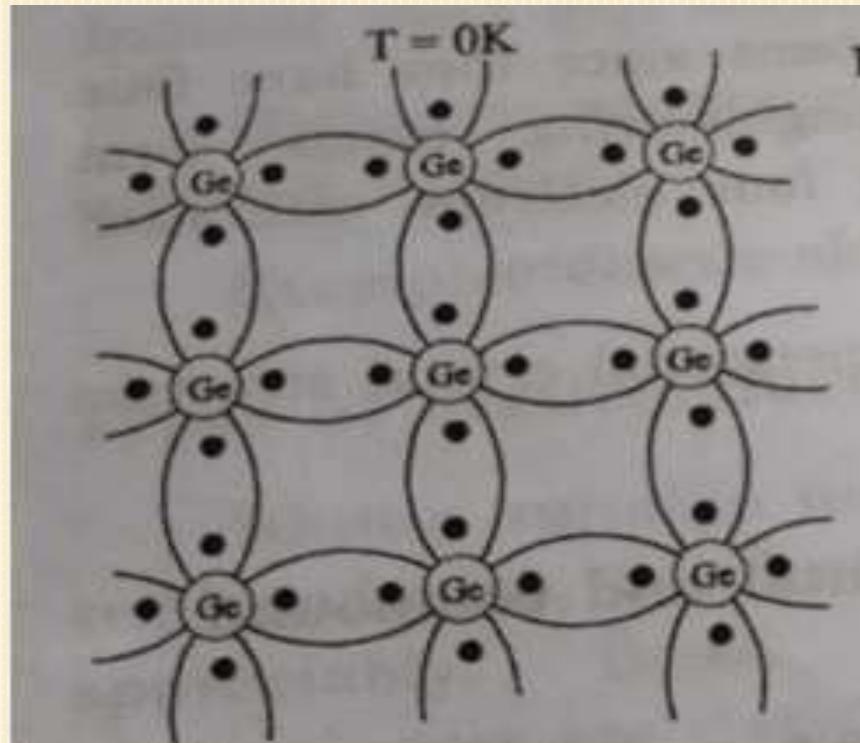
1. State the properties of a semiconductor.
2. What is meant by a semiconductor? Give an example.
3. What are the differences between intrinsic and extrinsic semiconductor?
4. What is meant by Energy band gap?
5. Why do we prefer Silicon for transistors and GaAs for laser diodes?
6. What is meant by hole current?
7. What do you mean by doping and dopants?
8. What are donor and acceptor energy levels?
9. Explain why electrons are majority carriers and holes are the minority carriers in an n type semiconductor.
10. Explain why holes are majority carriers and electrons are the minority carriers in a p type semiconductor.
11. Give the expression for Fermi energy of an intrinsic and extrinsic semiconductor at the temperature 0K.
12. Discuss the variation of Fermi level with temperature for P and n type semiconductors.
13. Give the expression for density of electrons in conduction band and holes in valence band.
14. Show the carrier concentration for an intrinsic semiconductor.
15. List out the applications of semiconductor.

# Carriers Generation and Recombination in Semiconductors

Carriers → free carriers or mobile carriers

Generation → Production or creation

Recombination → Annihilation or destruction

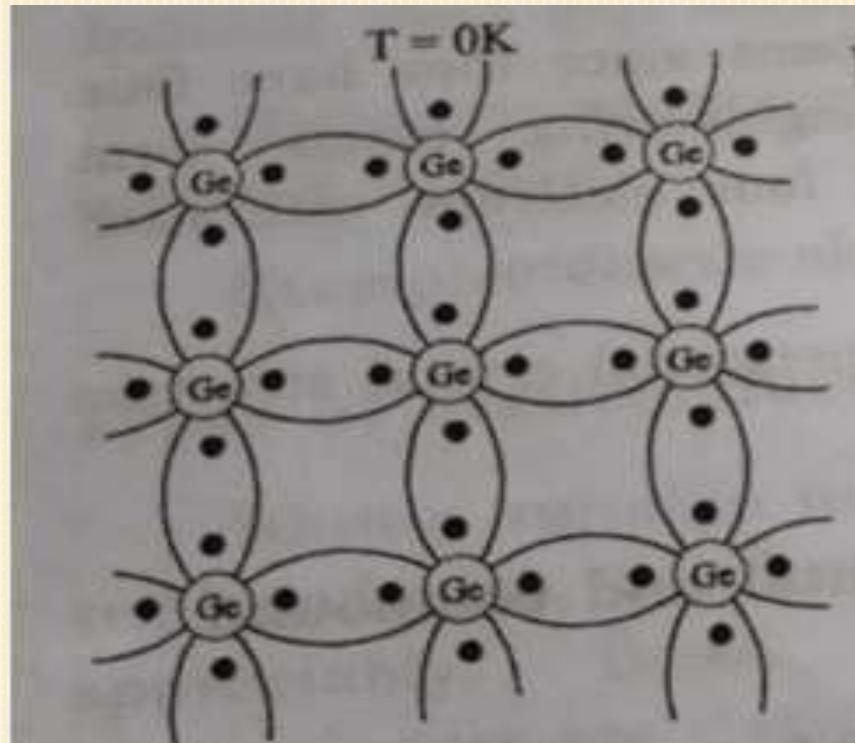


# Carriers Generation and Recombination in Semiconductors

Carriers → free carriers or mobile carriers

Generation → Production or creation

Recombination → Annihilation or destruction



# Carriers Generation in Semiconductors

Consider a Germanium atom,

When a temperature is given to a Ge crystal, the covalent bond breaks, electrons become free and can move inside the crystal freely. These free electrons from the valence band gains thermal energy and goes to the conduction band, leaving a hole in the valence band. In this way, the charge carriers are generated in the Ge crystal. Thus, **the process of generating electron hole pairs by exciting an electron from valence band to conduction band is called Carrier Generation.**

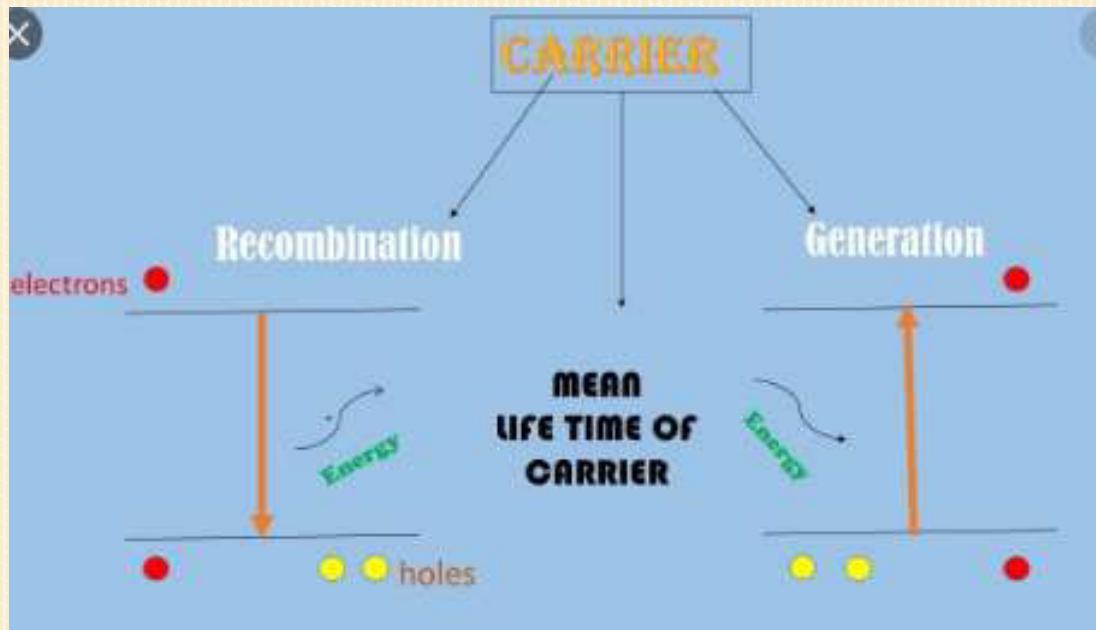
This carriers can be generated by providing heat energy or light energy or electrical energy.

This can be used in light detectors, such as photo detector, pin diode, Avalanche diode, photo diode, Solar cells etc.

# Carrier Recombination in Semiconductors

The reverse process of a carrier generation is called carrier recombination.

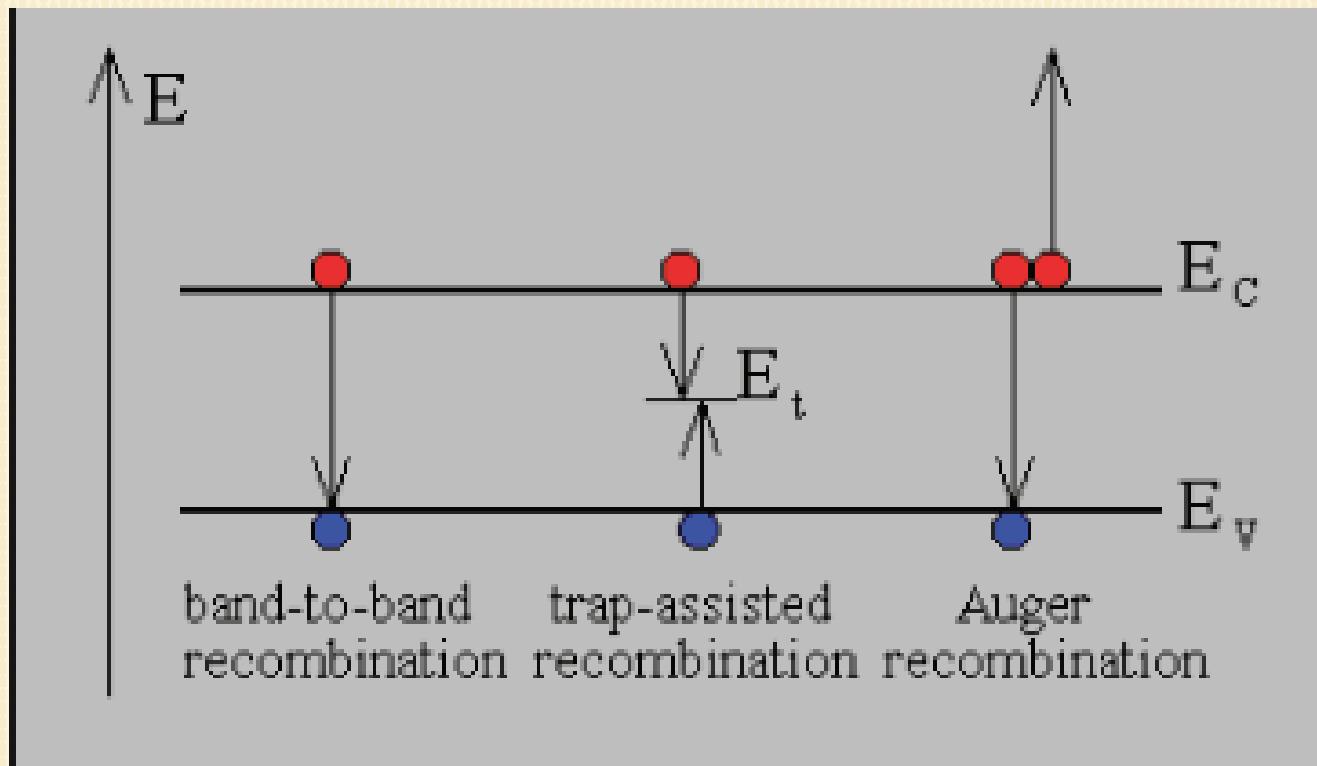
The process in which the electrons in the conduction band loses energy and reoccupies in the valence band, making both the charge carriers to annihilate with each other. This process is called Carrier Recombination.



# Carrier Recombination in Semiconductors

The Recombination process takes place in three steps as follows:

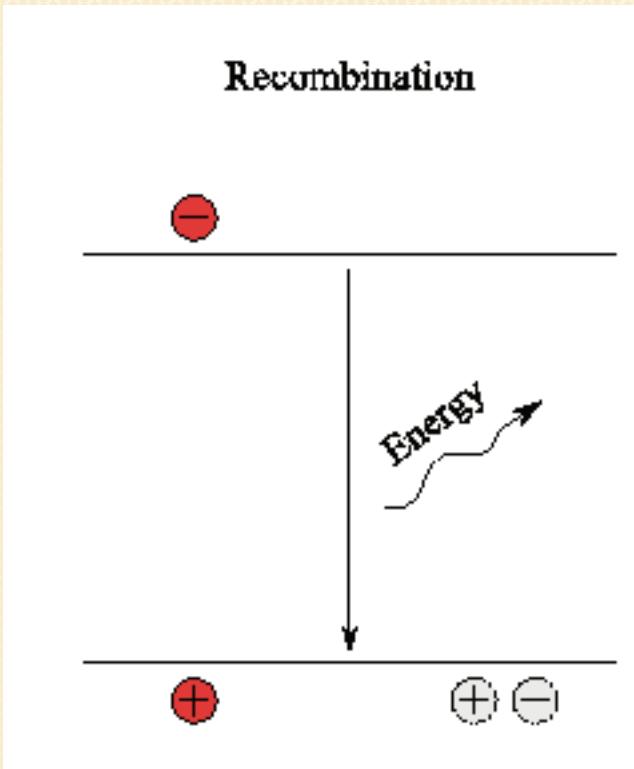
- Band to band recombination or radioactive recombination
- Trap assisted or Shockley Read Hall recombination
- Auger recombination



# Band to band Recombination in Semiconductors

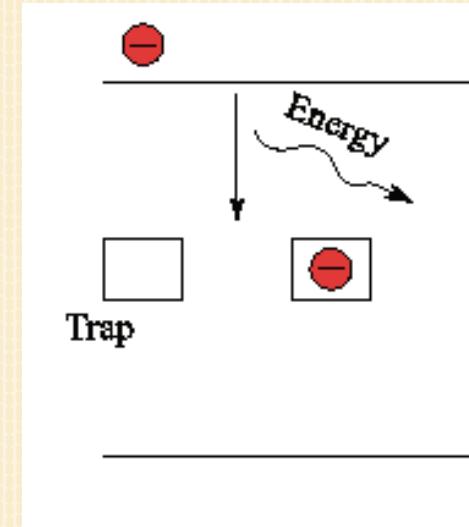
In a band to band recombination, An electron from the conduction band falls back to the valence band and releases its energy in the form of a photon (light).

The photon transition is known as a band-to-band recombination process.

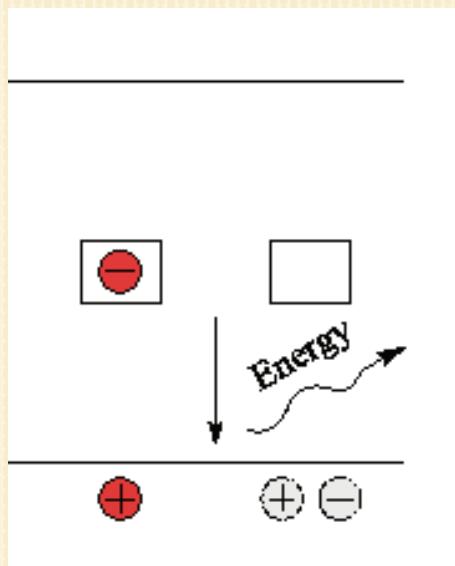


# Trap Assisted Recombination in Semiconductors

An electron from the conduction band is captured by an empty trap in the band-gap of the semiconductor. The excess energy of  $E_c - E_t$  is transferred to the crystal lattice through lattice vibrations (phonon emission).



Electron capture



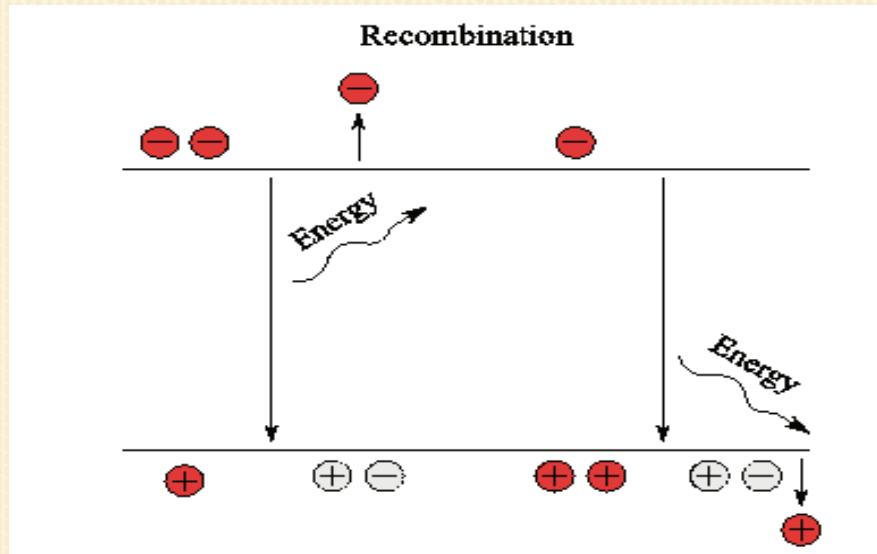
Hole capture

## Hole capture:

The trapped electron moves to the valence band and neutralizes a hole (the hole is captured by the occupied trap). A phonon with the energy  $E_t - E_v$  is generated.

# Auger Recombination in Semiconductors

In the Auger recombination three particles are involved. When an electron hole pair recombines, the excess energy is transferred to a third particle.



Auger recombination is a process in which an electron and a hole recombine in a band-to-band transition, but now the resulting energy is given off to another electron or hole. The involvement of a third particle affects the recombination rate so that we need to treat Auger recombination differently from band-to-band recombination.

# Carriers Transport in a Semiconductor

Carriers       Free electrons & holes

Transport       Net flow of electrons and holes in a material

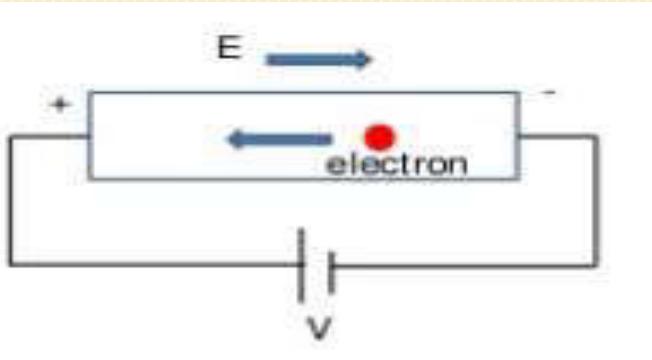
## Transport Mechanisms

There are two transport mechanisms of charge carriers:

- Carrier drift
- Carrier diffusion

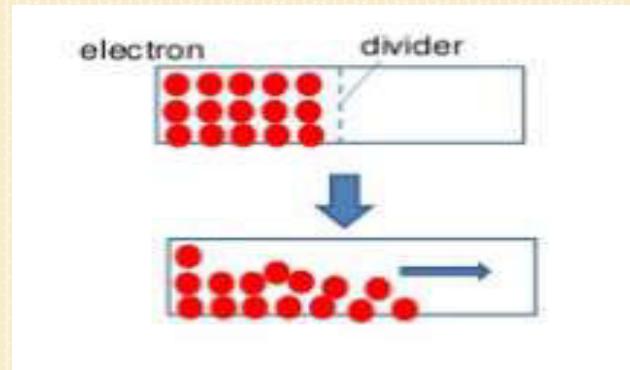
### Carrier

drift The net movement of charge carriers due to electric field is called carrier drift.



# Carrier Diffusion

The flow of charge carriers due to density gradients is called carrier diffusion.



# Scattering Mechanism of Charge Carriers

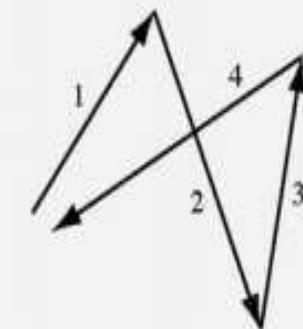
In a Semiconductor, the charge carriers do not follow a straight line path along the electric field lines. They bounce around a semiconductor and constantly changes direction and velocity due to scattering. This occurs when no electric field is applied.

# Scattering Mechanism of Charge Carriers

In the absence of electric field, the random motion of carrier occurs and is due to the thermal energy.

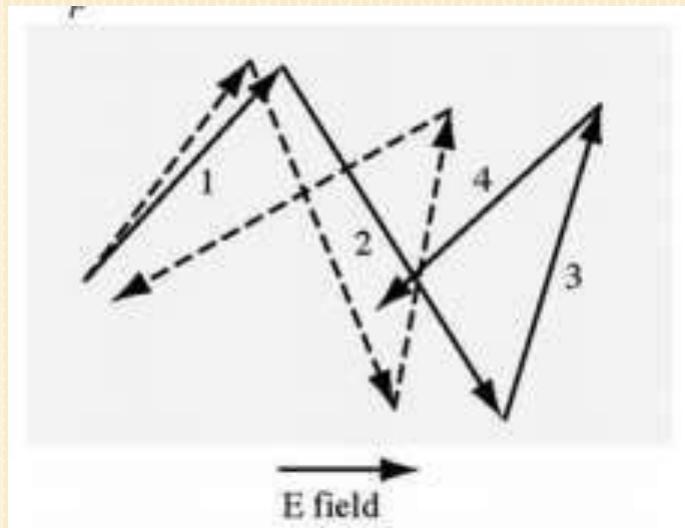
But no net displacement of carriers. The random thermal velocity is,

$$\frac{1}{2} m^* v_{th}^2 = \frac{3}{2} kT = 6.2245 \times 10^{-21} J$$



Under thermal equilibrium

When an electric field is applied, the random motion as well as net movement of carriers depends on the direction of electric field.



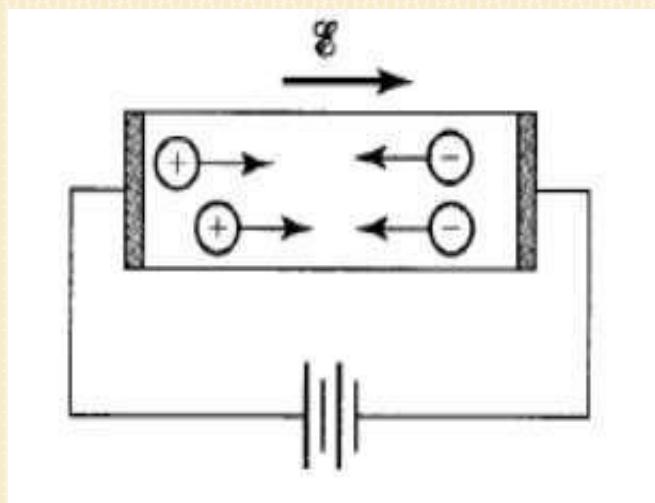
Hence the net carrier displacement and net velocity is along the direction of electric field. This velocity is called the drift velocity which gives drift current.

# Scattering Mechanism of Charge Carriers

In a semiconductor, charge carriers experience scattering due to impurities, lattices and imperfections on the surface. This type of scattering affects the transport of carriers.

## Carrier drift

When an electric field is applied to the crystal, electrons and holes experience a net acceleration in a direction in addition to its random motion.



As the charged particle accelerates, the velocity increases and then it suddenly collide with a vibrating atom and loses the gained velocity. The particle will again begin to accelerate and gain energy until it is again involved in a scattering process. The particle will gain an average drift velocity.

# Carrier drift

Net Force acting on a carrier is,  $F = \pm eE$  \_\_\_\_\_ (1)

The acceleration of the carrier is,  $a = \text{drift velocity} / \text{relaxation time}$

$$a = V_d / \tau \quad \text{--- (2)}$$

According to Newton's second law,  $F = ma$  \_\_\_\_\_ (3)

Substituting (2) in (3),  $F = m V_d / \tau \quad \text{--- (4)}$

Equating (1) & (4),  $m V_d / \tau = \pm eE$

Average drift velocity  $V_d = eE\tau / m \quad \text{--- (5)}$

Average drift velocity,  $v_d = \mu E$

Let Mobility,  $\mu = e\tau / m$

Mobility of electrons is  $\mu_e = e\tau / m_e$

Mobility of holes is  $\mu_h = e\tau / m_h$

# Carrier drift

We know, Current density,  $J = \sigma E$

Let Electrical Conductivity,  $\sigma = ne^2\tau / m$

Substituting  $\sigma$  in  $J$ ,

$$J = (ne^2\tau / m) E$$

$$J = n e (e\tau/m) E \text{ for electrons and holes}$$

Drift current for electrons,  $J = n e \mu_e E$  for electrons

Drift current for holes,  $J = p e \mu_h E$  for holes

$$J_{\text{Drift}} = J_{\text{electrons}} + J_{\text{holes}}$$

$$\text{Drift current, } J_{\text{Drift}} = n e \mu_e E + p e \mu_h E$$

# Electrical Conductivity & Resistivity

According to ohm's law, Current density,  $J = \sigma E$

$$J = E / \rho, \quad \text{since } \sigma = 1 / \rho$$

Electrical Conductivity,  $\sigma = n e (e\tau/m)$

$$\sigma = n e \mu_e + p e \mu_h$$

Electrical Resistivity,  $\rho = 1 / (n e \mu_e + p e \mu_h)$

*i.e. The reciprocal of resistivity is conductivity.*

# Carrier diffusion

In semiconductor, due to the non-uniformity of charge carriers (electrons/holes) the diffusion current arises even when no electric field is applied. It depends on the concentration gradient. This process is called carrier diffusion.

**Carrier diffusion** is a process where the charge carriers may be electrons or holes diffuse from higher carrier concentration to lower carrier concentration.



Electrons diffuse from higher concentration region ( $x = 0$ ) to lower concentration region ( $x = x$ )

# Carrier diffusion

At  $X = 0$ , free electrons at higher concentration region diffuse to  $X = x$  at lower concentration region. The net movement of charges produce current.

Thus for free electrons, the current  $J_n$  is produced in the direction opposite to the movement of electrons but for holes the current  $J_p$  is produced along the direction of movement of holes.

For electrons, Diffusion current is,  $J_n \propto \frac{dn}{dx}$

$$J_n = q D_n \frac{dn}{dx}$$

$\frac{dn}{dx}$  is the concentration gradient of free electrons

$D_n$  is the diffusion coefficient of free electrons

The current is flowing in the negative x-direction.

# Carrier diffusion

For holes, Diffusion current is,  $J_p \propto \frac{dp}{dx}$

$$J_p = -q D_p \frac{dp}{dx}$$

$\frac{dp}{dx}$  is the concentration gradient of holes

$D_p$  is the diffusion coefficient of holes

Diffusion Current density ,  $J_n = q D_n \frac{dn}{dx} - q D_p \frac{dp}{dx}$

Total Current density in a semiconductor is,

$J_{\text{Total}} = \text{Drift current} + \text{Diffusion current}$

$$J_{\text{Total}} = n e \mu_e E + p e \mu_h E + q D_n \frac{dn}{dx} - q D_p \frac{dp}{dx}$$

# **CARRIER GENERATION & RECOMBINATION, CARRIER TRANSPORT**

## **ASSIGNMENT – 2**

### **CARRIER GENERATION & RECOMBINATION, CARRIER TRANSPORT**

1. What is Carrier generation?
2. What is Carrier recombination?
3. What are the different methods of recombination process?
4. What is meant by photon & phonon?
5. Name the various transport mechanism in semiconductors.
6. What is meant by carrier drift?
7. What is meant by carrier diffusion?
8. What are the factors which affect the scattering process?
9. Give the drift current & diffusion current.
10. What is the resistivity & conductivity of a carrier drift?

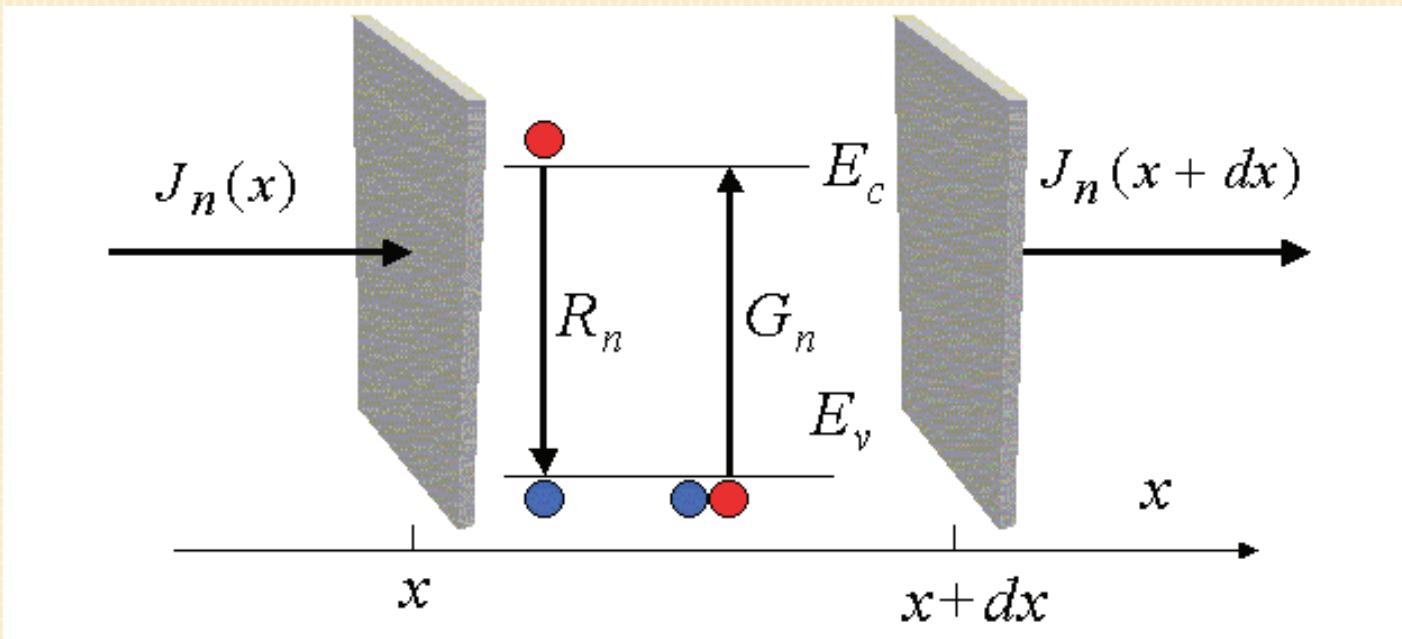
# Continuity Equation in a Semiconductor

In a semiconductor, the recombination generation process (R-G), the drift and diffusion simultaneously takes place in a semiconductor device.

The continuity equation describes, a change in carrier density over time is due to the difference between the incoming and outgoing flux of carriers plus the generation and minus the recombination.

The Continuity equation provides information about continuity of carriers in space and time. The flow of carriers, recombination and generation rates are shown in diagram.

# Continuity Equation in a Semiconductor



$$\frac{dn}{dt} = \left. \frac{dn}{dt} \right|_{\text{drift}} + \left. \frac{dn}{dt} \right|_{\text{diffusion}} + \left. \frac{dn}{dt} \right|_{R-G} + \left. \frac{dn}{dt} \right|_{\text{other}}$$

# Continuity Equation in a Semiconductor

Change in Carrier Concentration,

Where

$$J_n = J_n \text{ (drift)} + J_n \text{ (diffusion)}$$

Also,

$$\frac{dn}{dt} \Big|_{R-G} = -r_n$$

$$\frac{dn}{dt} = \frac{1}{q} \cdot \frac{dJ_n}{dt}$$

$$\frac{dP}{dt} = -\frac{1}{q} \cdot \frac{dJ_n}{dt}$$

Where  $r_n$  is the recombination of carriers

$$\frac{dn}{dt} \Big|_{\text{other}} = g_n^{2e}$$

Where  $g_n$  is the photo generation of carriers

# Continuity Equation in a Semiconductor

$$\frac{dn}{dt} = \frac{1}{q} \frac{dJ_n}{dx} + (G_n - R_n) \text{ for electrons.}$$

$$\frac{dp}{dt} = -\frac{1}{q} \frac{dJ_p}{dx} + (G_p - R_p) \text{ for holes.}$$

This is the general form of Continuity Equation.

This often yields two differential equations as a function of electron density, hole density and electric field,

$$\frac{dn}{dt} = \mu_n n \frac{dE}{dx} + \mu_n E \frac{dn}{dx} + D_n \frac{d^2 n}{dx^2} +$$

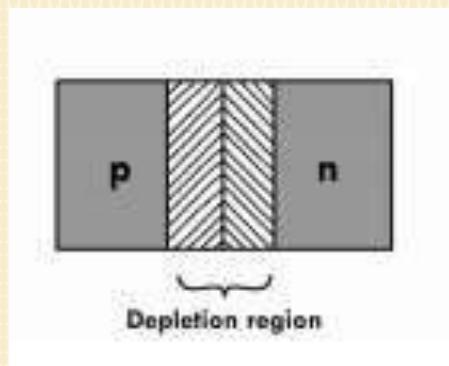
$$(G_n - R_n)$$

$$\frac{dp}{dt} = -\mu_p p \frac{dE}{dx} - \mu_p E \frac{dp}{dx} + D_p \frac{d^2 p}{dx^2}$$

$$+ (G_p - R_p)$$

# P-n junction diode

A p-n junction diode is a basic semiconductor device, which controls the flow of electric current in a circuit. A p-n junction diode is made when a suitable p type semiconductor is joined to n type semiconductor.

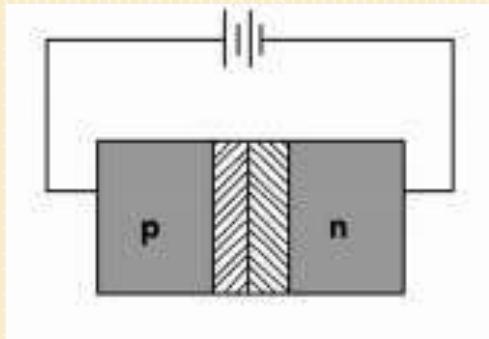


The process of giving potential difference across a p-n junction diode is called as biasing. The potential can be applied in two ways:

- Forward Biasing
- Reverse Biasing

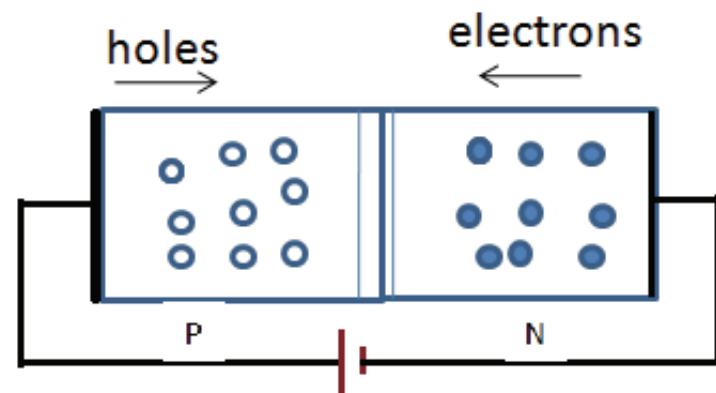
# Forward Biasing

When an external electric field is applied to a p-n junction diode, the current will flow through the junction. This is called **Forward biasing**.



A p-type material is connected to the positive electrode and n-type material is connected to the negative electrode.

When an electric field is applied, the electrons are moving towards p side and holes are moving towards n side. Hence the resultant field is weak and the barrier width is reduced at the junction.



# P-n junction diode

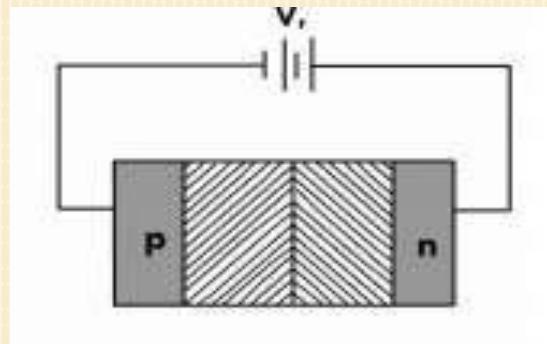
As the potential barrier becomes very small, a small forward voltage is sufficient to cancel the barrier. Once the barrier potential is eliminated, the junction resistance becomes zero. Thus, a large current will flow in a circuit and such current is called as forward current.

## Barrier Potential

It is the voltage developed by the junction due to the movement of charge carriers from one side to the other side.

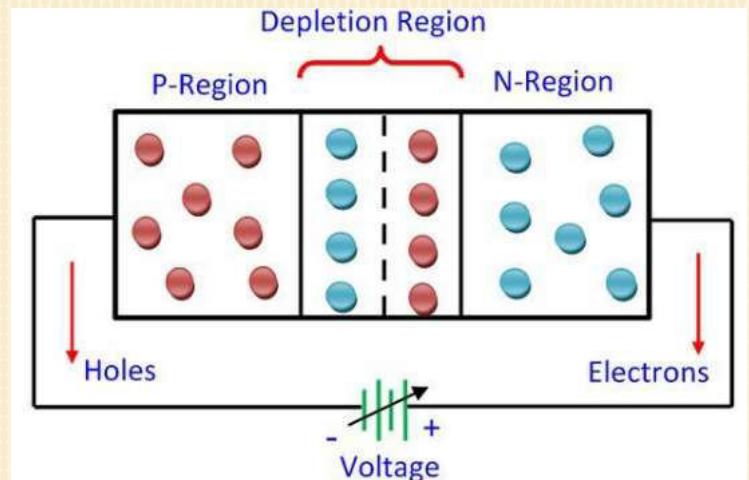
# Reverse Biasing

When an external electric field is applied to a p-n junction diode, the barrier is formed in the junction which restricts the current to flow through the junction. This is called **Reverse biasing**.



A p-type material is connected to the negative electrode and n-type material is connected to the positive electrode.

When an electric field is applied, the electrons and holes movement is reduced, so junction area is increased and hence barrier potential is increased. The diode offers very high resistance.



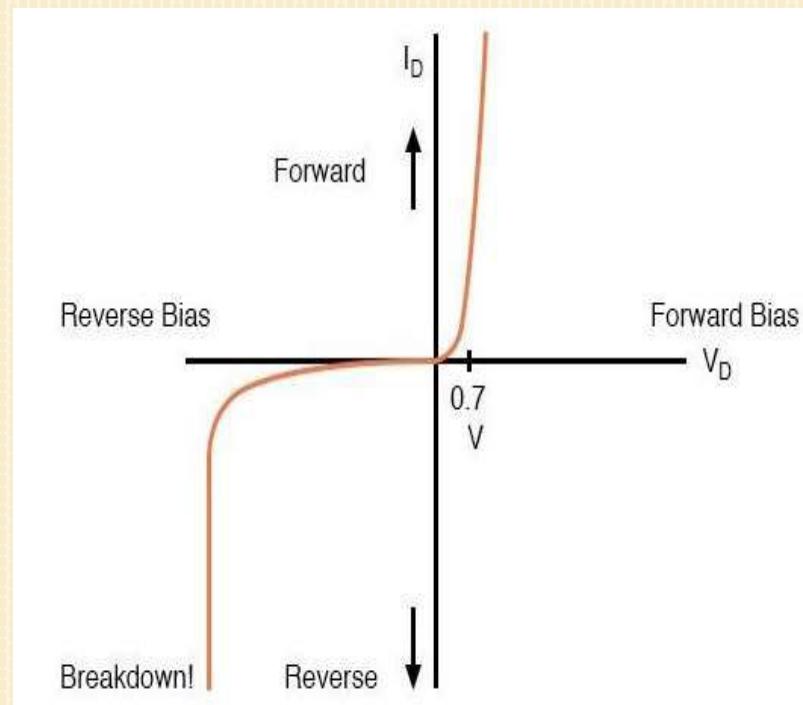
# Reverse Biasing

No net current flows in the circuit due to high resistance path. Also a small current will flow due to the movement of minority carriers.

This current is known as reverse current.

## I-V Characteristics of p-n junction diode

The I-V characteristics of a P-n junction is the curve drawn between voltage across x-axis and the current along y-axis. This can be studied under forward biasing and reverse biasing.



# I-V Characteristics of p-n junction diode

- A voltage is applied to a p-n junction diode under forward biasing. As the voltage is increased from zero, and increases gradually, the barrier potential is completely eliminated. The current starts flowing in the circuit. The current increases very slowly with the increase in forward voltage and is shown in figure.
- The curve is non linear because the external voltage should overcome the barrier potential.
- Once the external voltage exceeds the barrier potential, the p-n junction diode behaves like a conductor and the current increases very sharply with the increase in applied voltage.
- The forward voltage at which the current through the junction starts increasing rapidly is known as **Knee voltage**.

# I-V Characteristics of p-n junction diode

- A voltage is applied to a p-n junction diode under reverse biasing.
- As the voltage increases, a small increase in the current occurs. At a particular voltage called the breakdown voltage, the current flowing through the circuit rises and a certain rise in the curve occurs.
- At this breakdown voltage, the minority carriers get enough energy to break the junction and hence the diode allows the current.
- **Breakdown Voltage** is the reverse voltage of a p-n junction diode at which the junction breaks down with sudden rise in the reverse current.

# Metal Semiconductor – Ohmic & Schottky

Contacts When a metal and a semiconductor are in contact with each other, there exists a potential barrier between them. This barrier prevents most of the charge carriers to pass from one to the other. Only very few charge carriers may have enough energy to get over the barrier and to cross to the other material.

When a bias is applied to the metal - semiconductor junction, it can make two effects possible, i.e.

- It can make the barrier to appear lower from the semiconductor side
- It can make the barrier to appear higher from the semiconductor side

Here, the biasing does not changes the barrier height from the metal side. This is called as a **Schottky barrier or rectifying contact**, where the junction conducts for one bias polarity, but not the other. Almost all metal-semiconductor junctions will exhibit this rectifying behavior.

Schottky contacts are used to make good diodes and transistors.

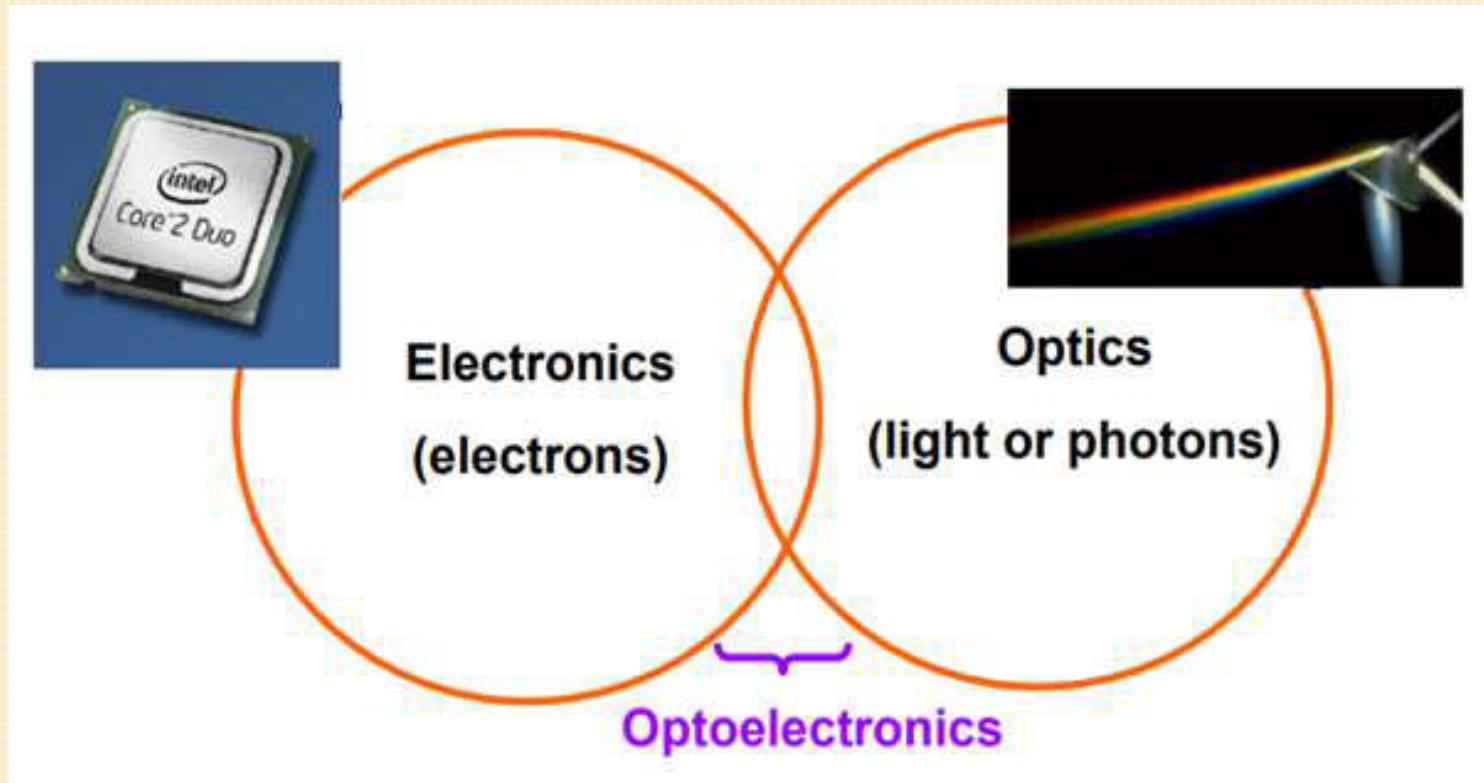
# Metal Semiconductor – Ohmic Contacts

**Metal – Semiconductor ohmic contacts are used for getting signals into and out of a semiconductor device. Ohmic contacts conduct the same for both polarities, because they obey ohm's law.**

**This contact makes the barrier height low & narrow.**

# Opto Electronics

Opto electronics is the study and application of electronic devices that interact with light.



# Semiconductors interest in Opto Electronics

Optoelectronics deals with the optical interaction on the electronic responses in some specific optically active semiconducting materials. The semiconducting materials are preferred due to the variation in their electrical conductivity by varying change in temperature, optical excitation and the presence of impurity content in them. The devices which support this type of interaction are known as **optoelectronic devices**.

In general, optoelectronics, will **convert optical energy into electrical energy or electrical energy into optical energy**.

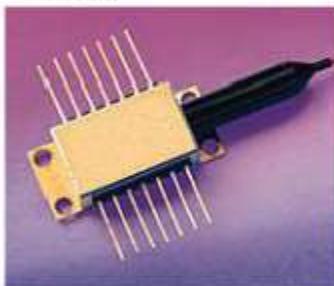
The important parameters of the semiconductors are:

- It has the electrical conductivity between metals and insulators
- It has the moderate energy gap, between valence conduction band.

This parameter determines, whether a particular light wavelength will be absorbed, transmitted or emitted. Also preferred semiconducting materials for making opto electronic devices.

# Examples of Opto Electronic Devices

Telecommunication  
laser



Newport.com

Blue laser



TDK

Optical fiber



Corning

LED traffic lights



Rsc.org

Photodiodes



Hamamatsu

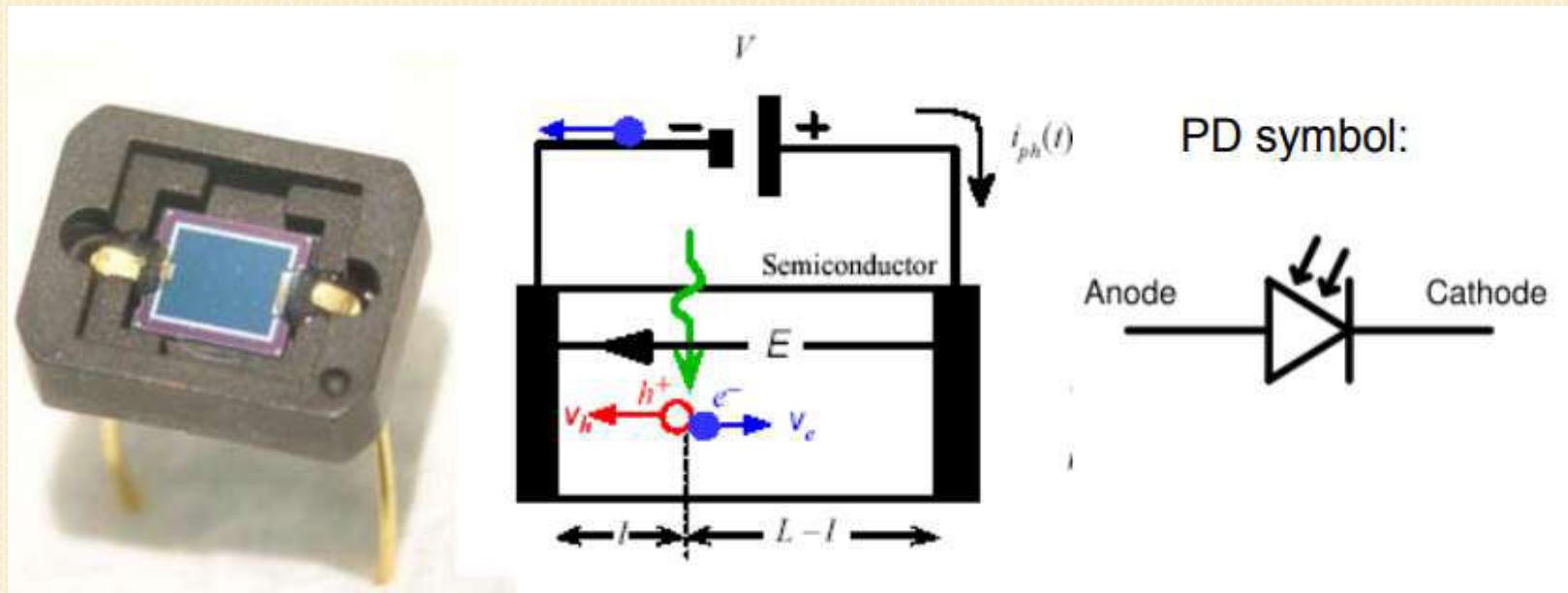
Solar cells



Wikipedia

# Examples of Opto Electronic Devices

# PHOTO DIODE



A photo diode is a semiconductor diode that functions as a photo detector. When a photon of sufficient energy strikes the diode it excites an electron thereby creating a mobile electron and a positively charged electron hole.

# Examples of Opto Electronic Devices

## LED

LED is a semiconductor diode that emits incoherent light over relatively wide spectral range, when electrically under forward biased.

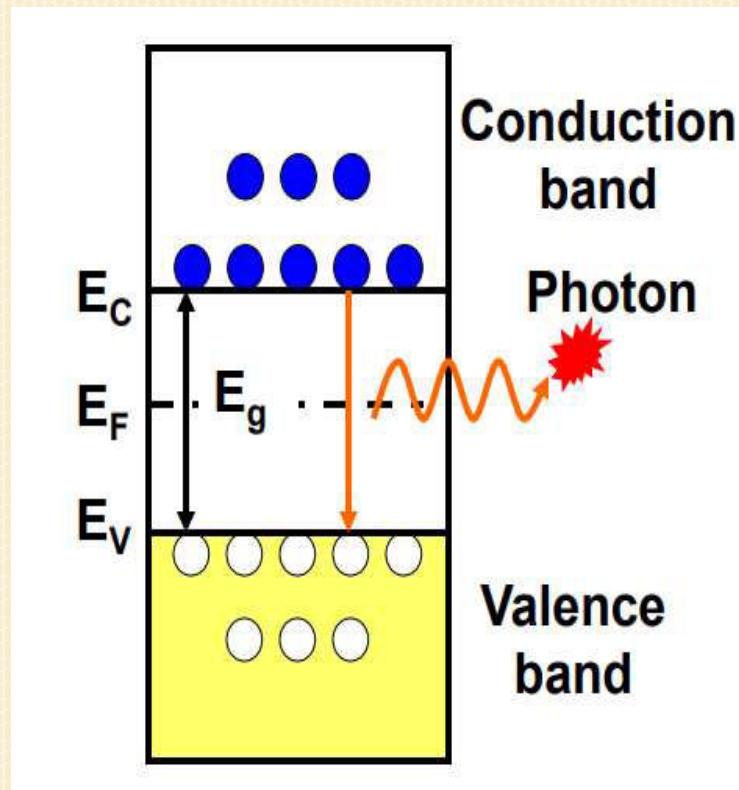


Photo Emission in Semiconductors

Some Semiconducting materials are Si, Ge, GaAs, InP, InGaAs, AlGaAs etc

# LED – Light Emitting

## Diode

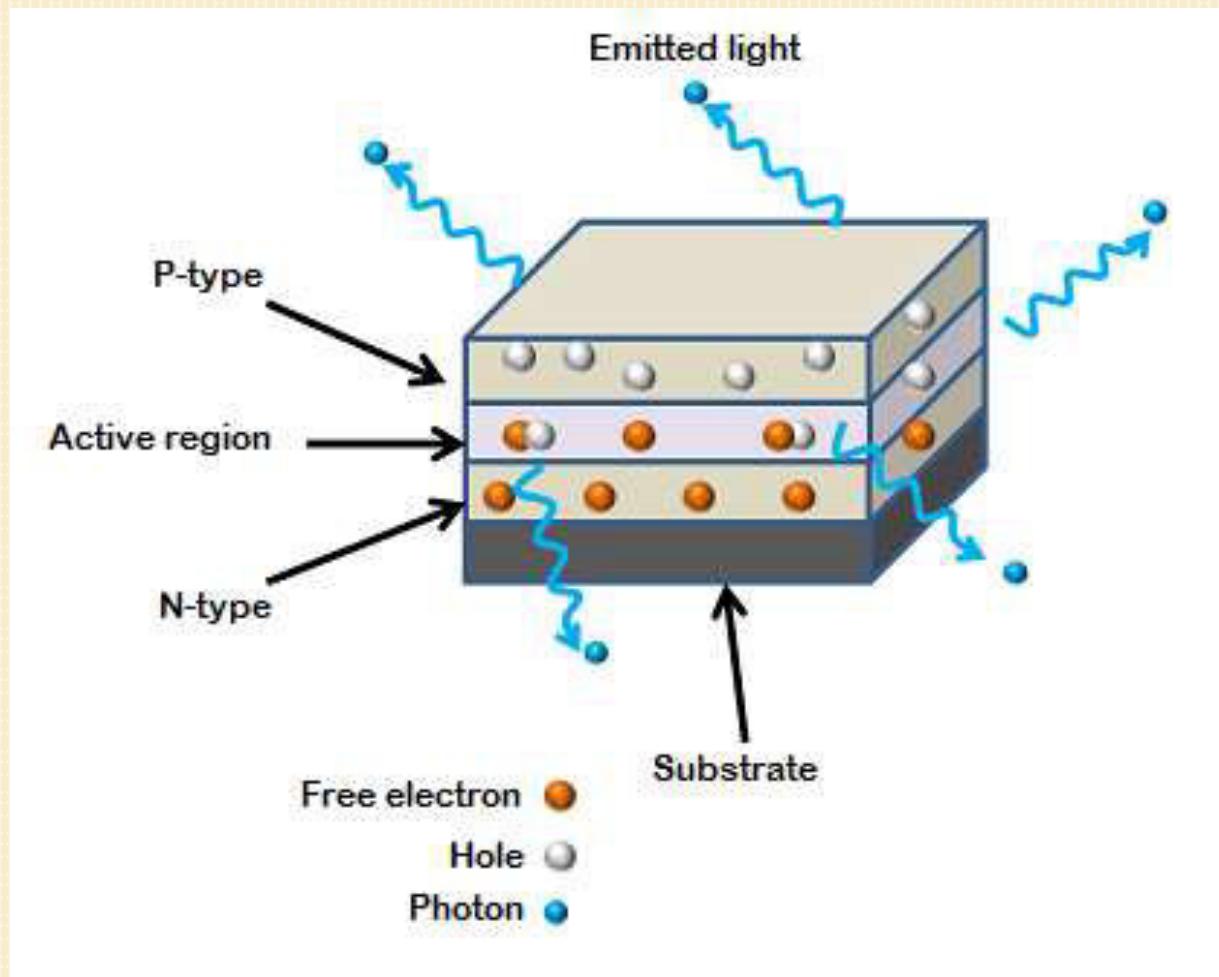
**LED** is a semiconductor P-n junction diode which converts electrical energy into light energy under forward biasing. It emits light both in IR and visible region. LED allows the flow of current in its forward direction while it blocks the flow in the reverse direction. Based on the semiconductor material used and the amount of doping, an LED will emit a coloured light at a particular spectral wavelength when forward biased.

### Principle:

- When LED is forward biased, the majority charge carriers from n region moves towards p, like wise from p region moves towards n region and makes excess minority carriers in the n and p regions.
- These minority carriers diffuses through the junction and recombines with the majority charge carriers in n and p region and produces light.

# LED – Light Emitting Diode

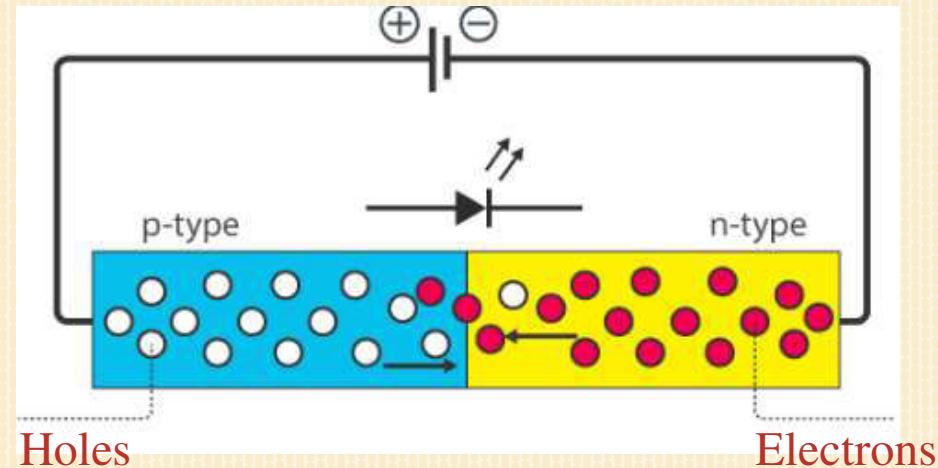
## Construction of LED



# LED – Light Emitting

## Diode

When LED is forward biased,  
the electrons from n region and  
holes from p region are pushed  
towards the junction.



- When the free electron reaches the depletion region, it recombines with the holes and holes from the p region recombines with the electrons in the depletion region.
- Due to the recombination of electrons and holes in the depletion region, the width of the depletion region decreases. Hence, more charge carriers crosses the p-n junction.

# LED – Light Emitting

## Diode

Some charge carriers from p and n region crosses the junction before recombination itself.

- Therefore, recombination occurs in the depletion region as well as in the p and n region.
- Hence more and more light photons are emitted.

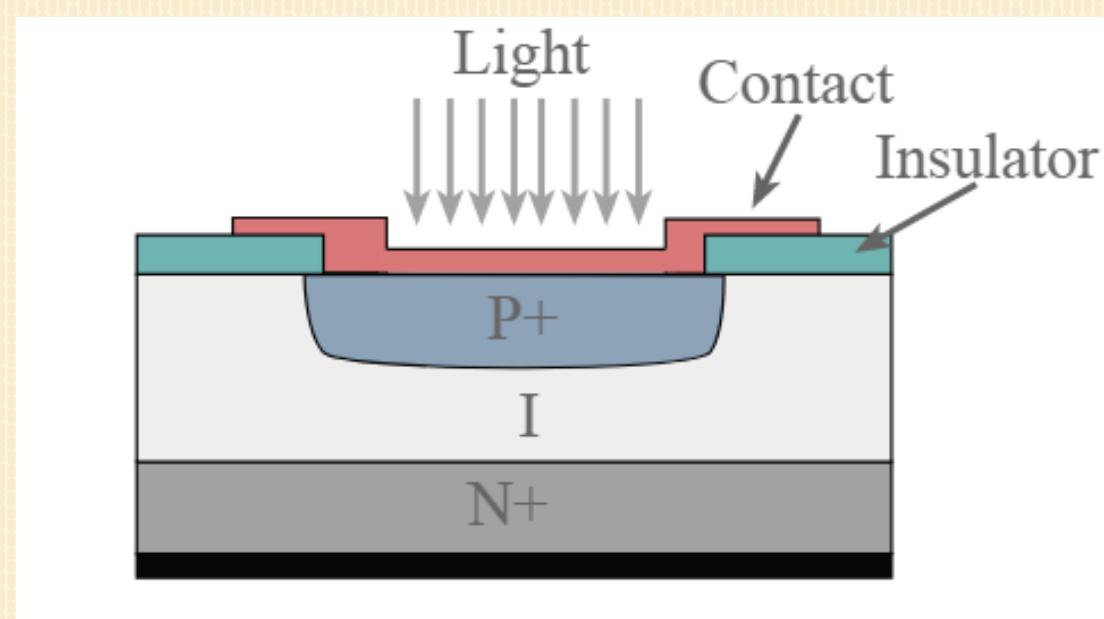
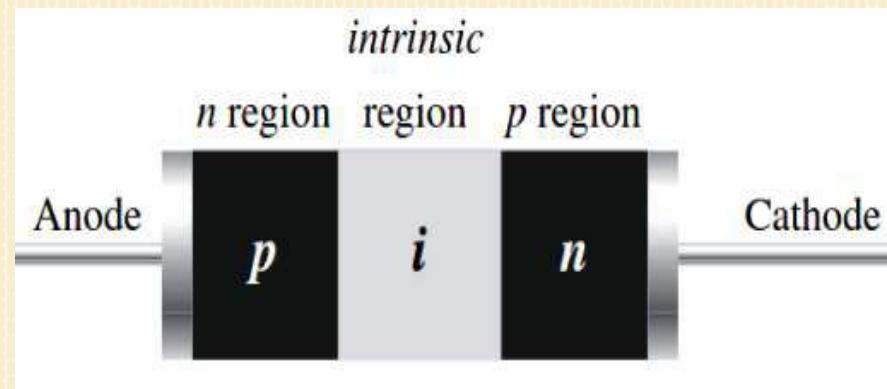
## Uses of LED

1. LED converts electrical energy into light energy
2. Cost is low
3. Fabrication is easy
4. They are used in the manufacture of signal lamps, displays etc.
5. The IR –LED is a potential source for optical fiber communication.

# PIN Photo Diode

- ❖ The PIN Photo diode converts light energy into electrical energy. The diode works in reverse bias
- ❖ A very high reverse bias voltage is applied to a P-I-N photo diode.
- ❖ The intrinsic region is lightly doped with n-type material and so less mobile charges are there.
- ❖ The width of the depletion region is increased.
- ❖ When an incident photon energy is greater than or equal to bandgap energy, incidents on the depletion region, the electron hole pair is created due to the absorption of photons.
- ❖ The mobile charges accelerated by the applied voltage which rise to photo current.
- ❖ Thus it acts as a linear device, because the photo is directly proportional to the optical power incident on the P-I-N diode.

# PIN Photo Diode

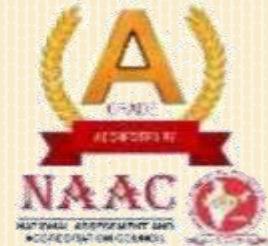


# QUESTIONS - Devices

- 1. What is a p-n junction ?**
- 2. Define forward and reverse current?**
- 3. What is known as barrier potential?**
- 4. What is known as knee voltage?**
- 5. What are the two mechanisms of breakdown in a p-n junction junction?**
- 6. What is a reverse saturation current?**
- 7. Name some optoelectronic devices.**
- 8. What is the function of metal –semiconductor junction in schottky and ohmic contact?**
- 9. What is the working principle of optoelectronic devices?**
- 10. Why semiconductor materials are commonly preferred for making opto electronic devices?**
- 11. What is LED?**
- 12.What is photo diode?**



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## UNIT - II

# SEMICONDUCTOR PHYSICS



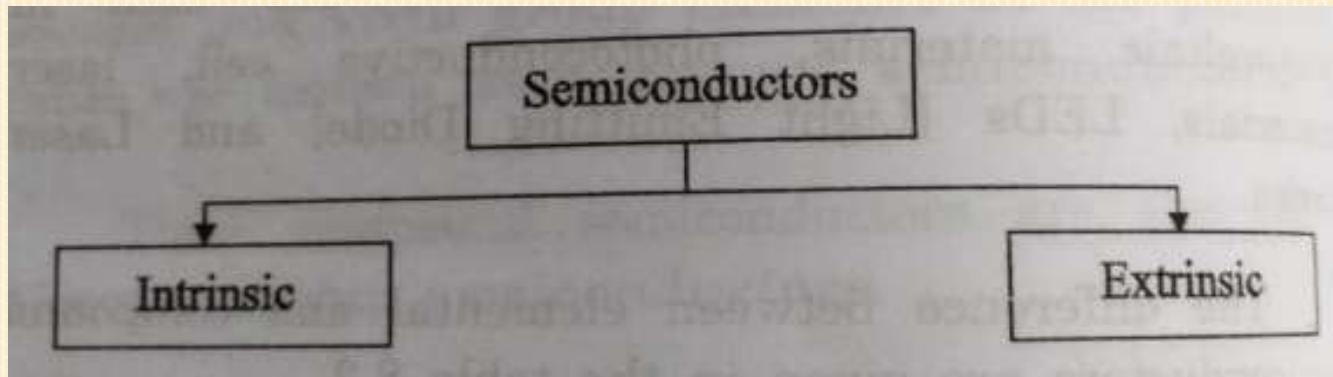
PRESENTED BY

DR. C. RATHIKA THAYA KUMARI,  
Associate Professor,  
Department of Physics

# Types of Semiconductors

When a suitable impurity is added to a pure semiconductor, its electrical conductivity changes. Based on this property, Semiconductors are classified into,

- Intrinsic Semiconductor or Pure Semiconductor
- Extrinsic Semiconductor or impure Semiconductor



# Intrinsic Semiconductor

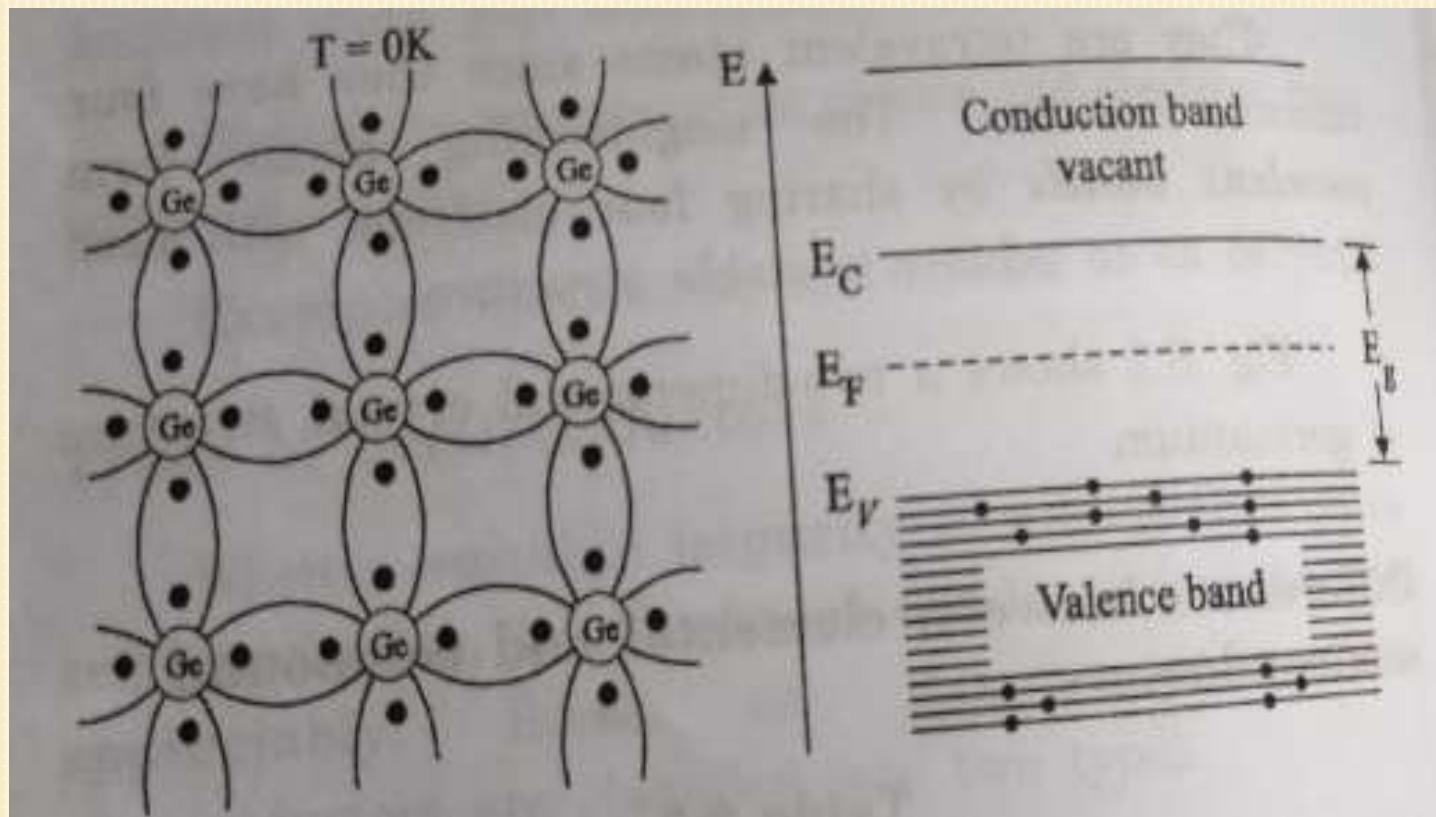
A semiconductor in extremely pure form without the addition of impurities is known as an intrinsic semiconductor. Its electrical conductivity can be changed due to thermal excitation.

**Examples:** Germanium, Silicon

- They belong to IV<sup>th</sup> group of the periodic table.
- Germanium has 32 electrons and Silicon has 14 electrons in their atomic structures.
- They are tetravalent atoms since they have four valence electrons.
- The neighboring atoms form covalent bonds by sharing four electrons with each other so as to achieve stable structure.

# Intrinsic Semiconductor

- At very low temperature 0K, no free electrons are available for conduction.
- Semiconductor behaves as an insulator at very low temperature

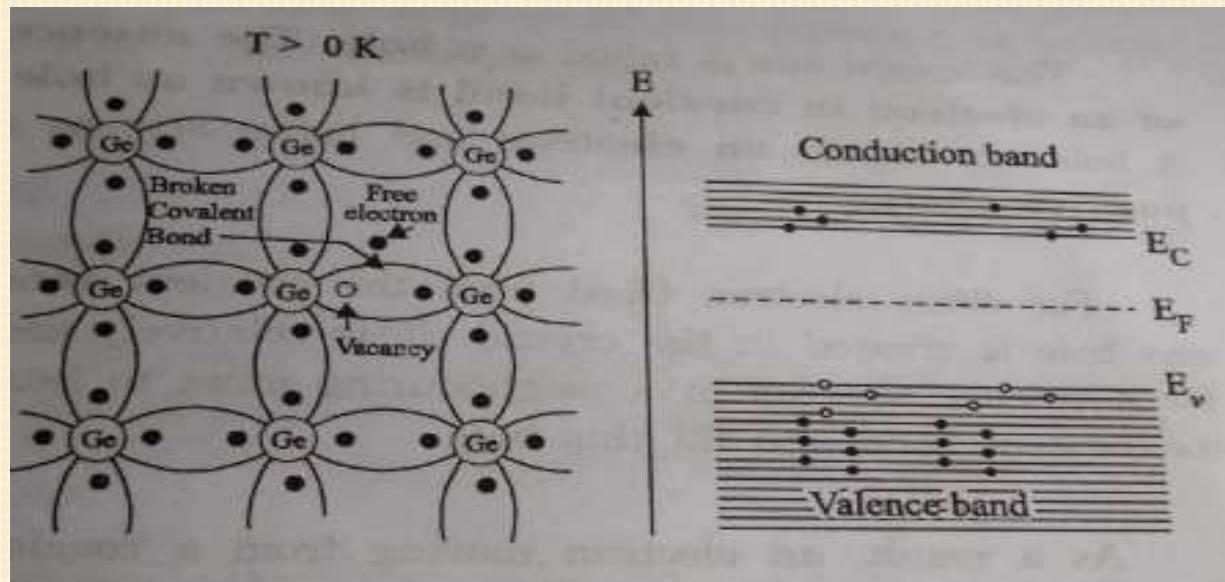


## Charge Carriers - Intrinsic Semiconductor

- To get free electrons, the covalent bonds must be broken.
- When the temperature is increased, some of the electrons acquire sufficient energy to break the covalent bonds.
- Once the electrons are liberated from the bond, they become free electrons.
- Such free electrons move randomly through the crystal.
- When an electric field is applied, free electrons acquire directional motion and contribute electrical conductivity.
- The energy required to break a covalent bond and to set an electron free is equal to the band gap energy .
- It is 0.72 eV for germanium and 1.1 eV for Silicon.

# Charge Carriers - Intrinsic Semiconductor

- When an electron acquires energy  $E_g$  it jumps from valence band to conduction band. As a result, a **vacant site** is created in valence band. This vacant site is called as a **hole**.
- The absence of an electron in covalent bond is known as hole.
- A hole can attract an electron and act as a positive charge.

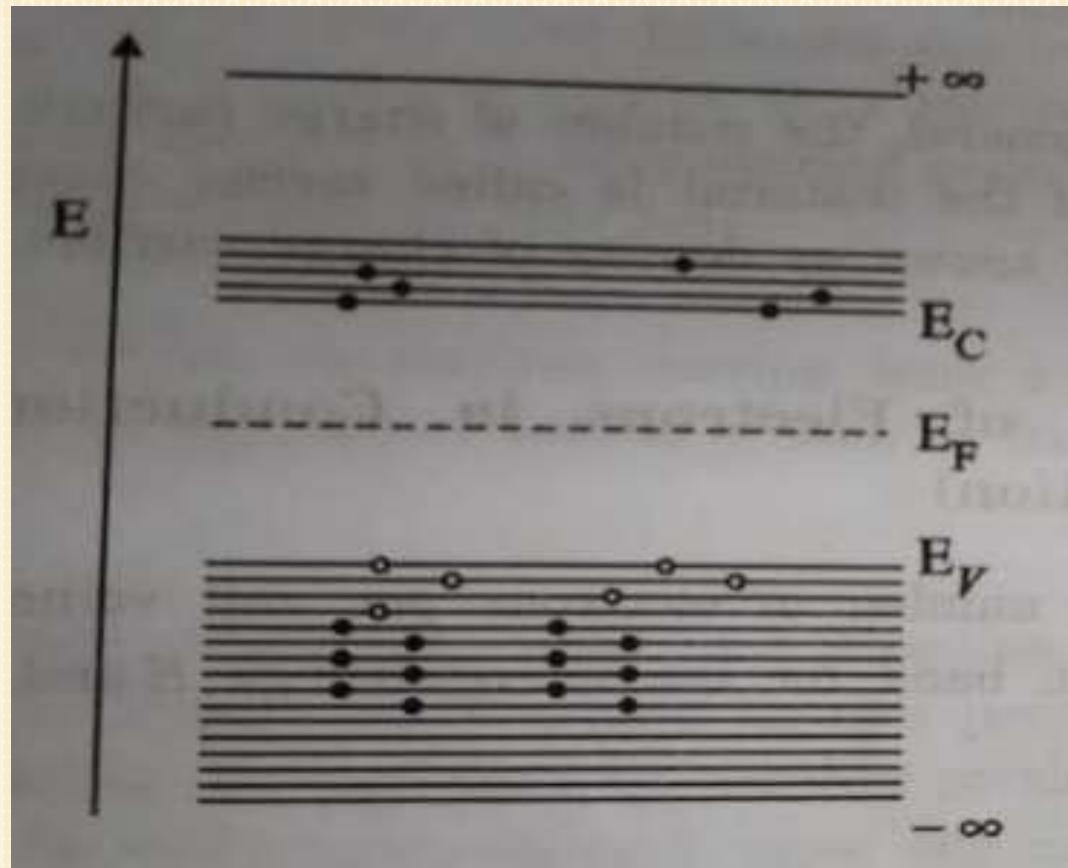


## Charge Carriers - Intrinsic Semiconductor

- For every electron freed from the covalent bond, one hole is created. As a result, an electron moving from a covalent bond to fill a hole leaves behind a hole in its original position.
- The hole effectively moves in a direction opposite to the electron.
- The hole in its new position may now be filled by an electron from another covalent bond and move one step in the direction opposite to the motion of the electron.
- Hence, in an intrinsic semiconductor, the current conduction is due to the movement of electrons and holes.
- Therefore, Number of electrons is equal to the Number of holes at any temperature.

# Carrier Concentration in an Intrinsic Semiconductor

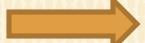
The number of charge carriers per unit volume of the material is called Carrier concentration (density of charge carriers).



Energy Band Diagram  
for intrinsic  
semiconductor

# Carrier Concentration in an Intrinsic Semiconductor

Number of electrons in the conduction band (n) is



$$n = 2 \left( \frac{2 \pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_C) / kT}$$

$$p = 2 \left( \frac{2 \pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F) / kT}$$



Number of holes in the valence band (p) is

In an intrinsic semiconductor, Number of electrons in the conduction band is equal to the Number of holes in the valence band. i.e.  $n = p = n_i$

where  $n_i$  is the intrinsic carrier concentration.

$$np = n_i * n_i = n_i^2$$

# Carrier Concentration in an Intrinsic Semiconductor

Substituting the expressions for n & p we get,

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

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

$$n_i^2 = 4 \left( \frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} e^{-E_\epsilon/kT}$$

where  $E_c - E_v = E_g$  is the forbidden energy gap.

$$n_i = 2 \left( \frac{2\pi kT}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_\epsilon/2kT}$$

## Variation of Fermi energy level with Temperature in an Intrinsic Semiconductor

For an intrinsic semiconductor, number of electrons will be same as that of number of holes.  $n_e = n_h$

Equating the values of  $n_e$  and  $n_h$  we get,

$$\left( m_e^* \right)^{3/2} e^{(E_F - E_c)/K_B T} = \left( m_h^* \right)^{3/2} e^{(E_v - E_F)/K_B T}$$

$$\left\{ \frac{m_h^*}{m_e^*} \right\}^{3/2} = \frac{e^{(E_F - E_c)/K_B T}}{e^{(E_v - E_F)/K_B T}}$$

$$= e^{(E_F - E_c - E_v + E_F)/K_B T}$$

# Variation of Fermi energy level with Temperature in an Intrinsic Semiconductor

$$\left( \frac{m_h^*}{m_e^*} \right)^{3/2} = e^{(2E_F - (E_v + E_c)) / K_B T}$$

Taking log on both sides,

$$3/2 \log \left( \frac{m_h^*}{m_e^*} \right) = \frac{[2E_F - (E_v + E_c)]}{K_B T}$$

$$2E_F = E_c + E_v + \frac{3}{2} K_B T \log \frac{m_h^*}{m_e^*}$$

$$E_F = \frac{E_c + E_v}{2} + \frac{3}{4} K_B T \log \left( \frac{m_h^*}{m_e^*} \right)$$

# Variation of Fermi energy level with Temperature in an Intrinsic Semiconductor

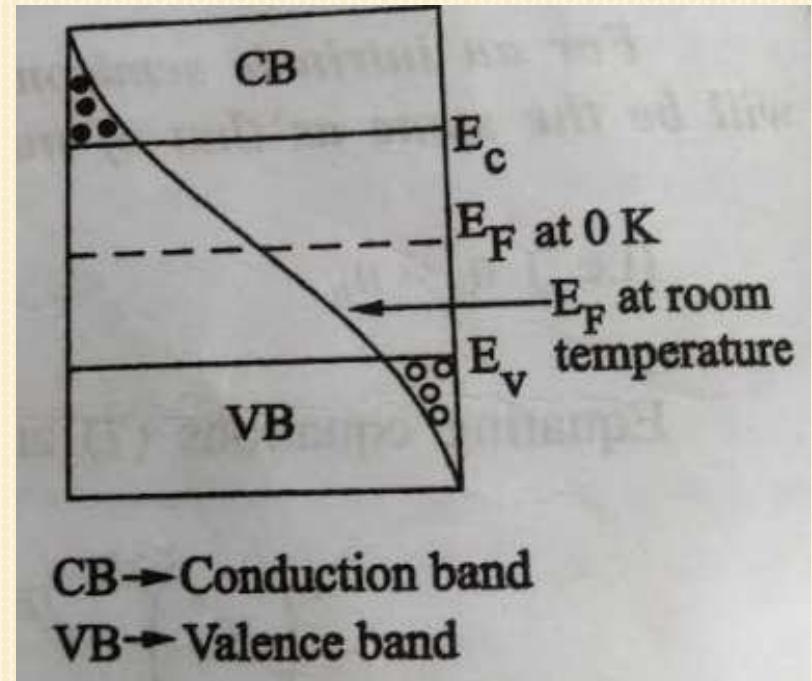
If  $m_h^* = m_e^*$ , then  $\log \frac{m_h^*}{m_e^*} = 0$  [ $\because \log 1 = 0$ ]

Fermi Energy of an intrinsic semiconductor is

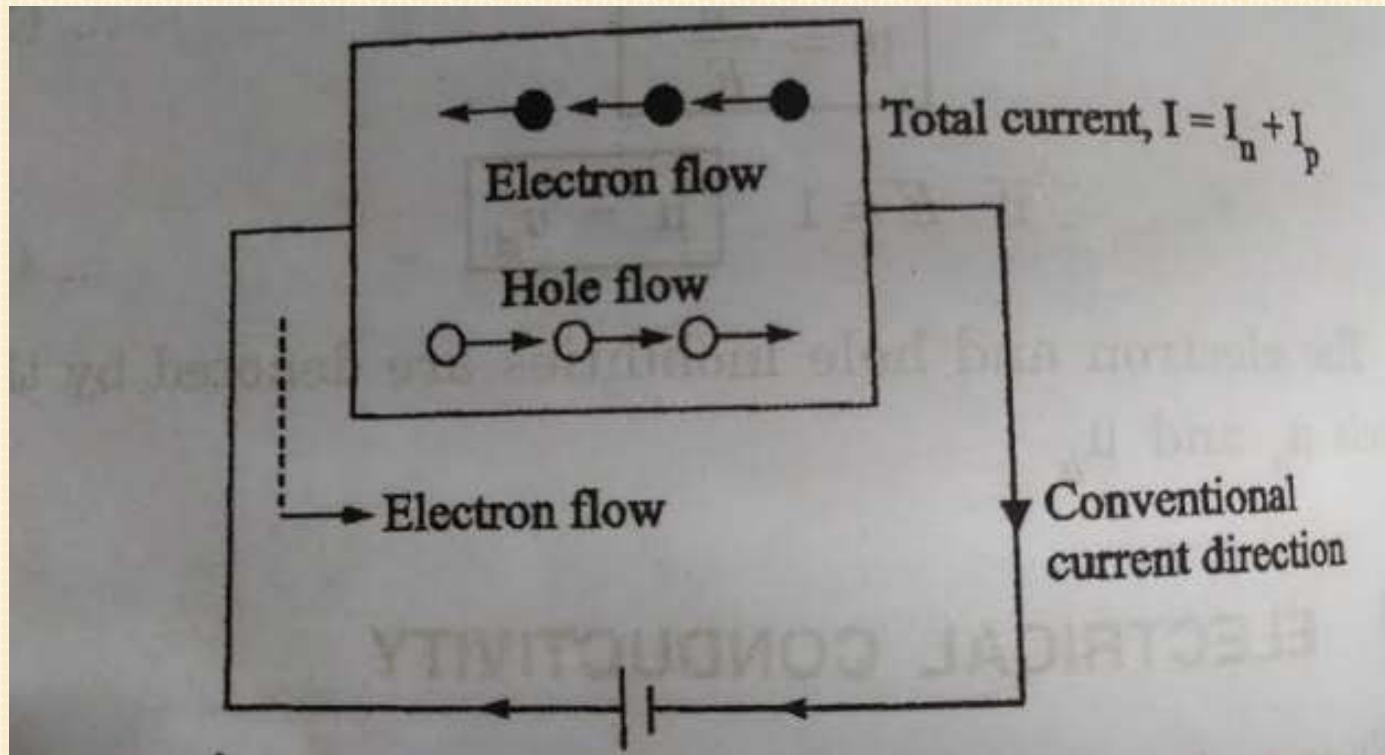


$$E_F = \frac{E_c + E_v}{2}$$

- The Fermi level lies in the midway between Ec and Ev at T=0K.
- Also in case  $m_h^* > m_e^*$  and the Fermi energy level slightly increases with the increase in temperature.



# Conduction of electrical current in an Intrinsic Semiconductor



The charge carriers in a semiconductor are **electrons** and **holes**. Both the charge carriers will take part in the current conduction



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## UNIT - II

# SEMICONDUCTOR PHYSICS

PRESENTED BY

DR. C. RATHIKA THAYA KUMARI,

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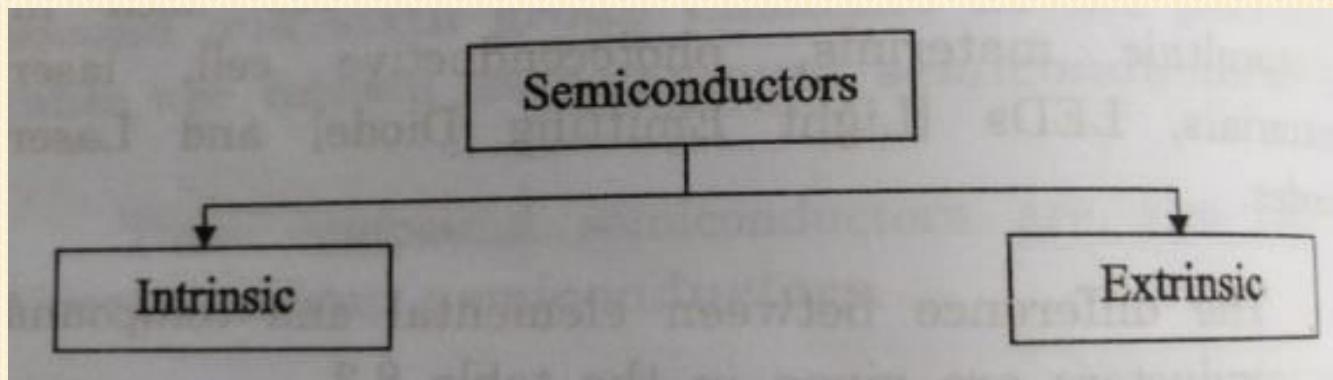
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# Intrinsic Semiconductor

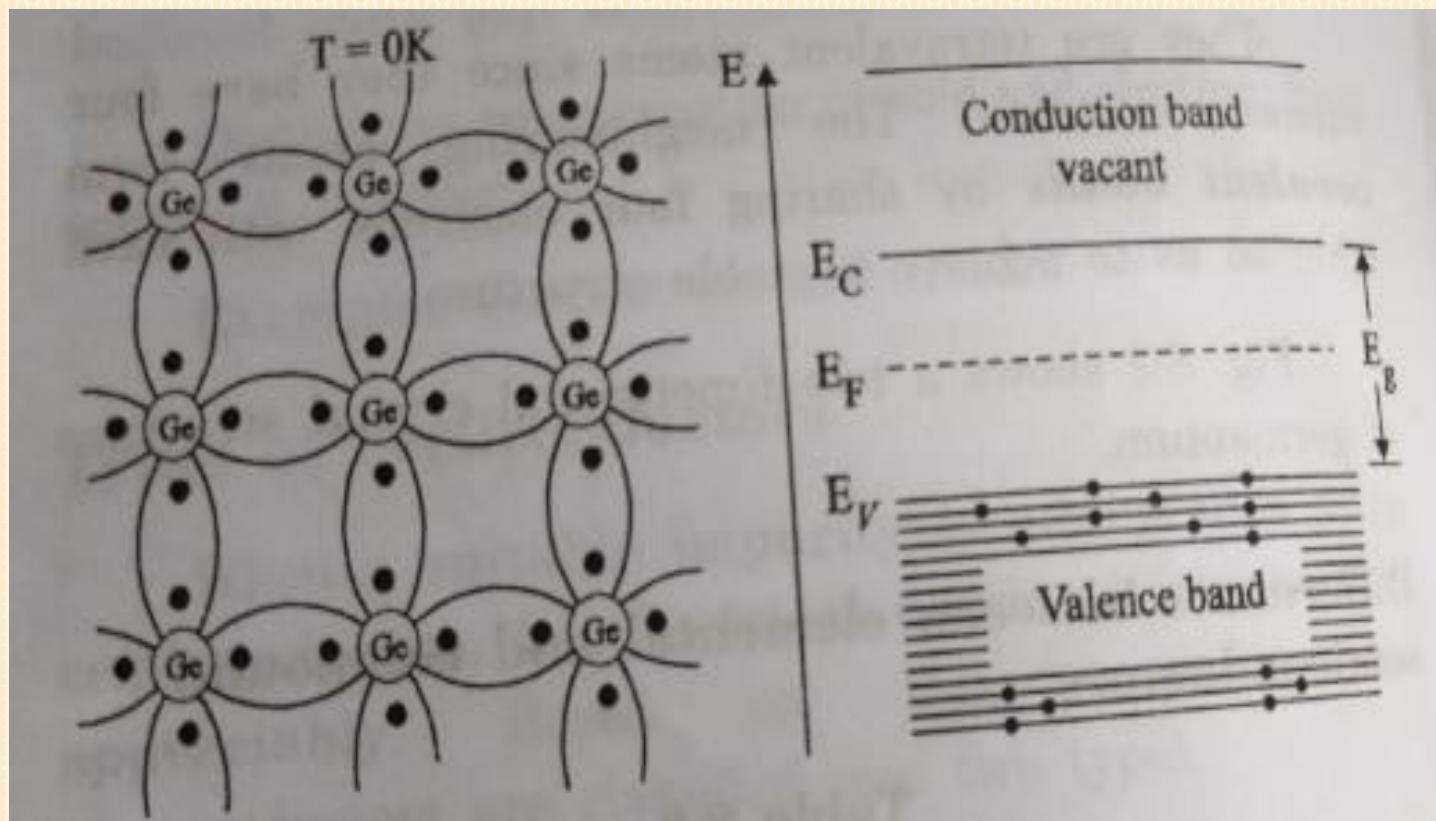
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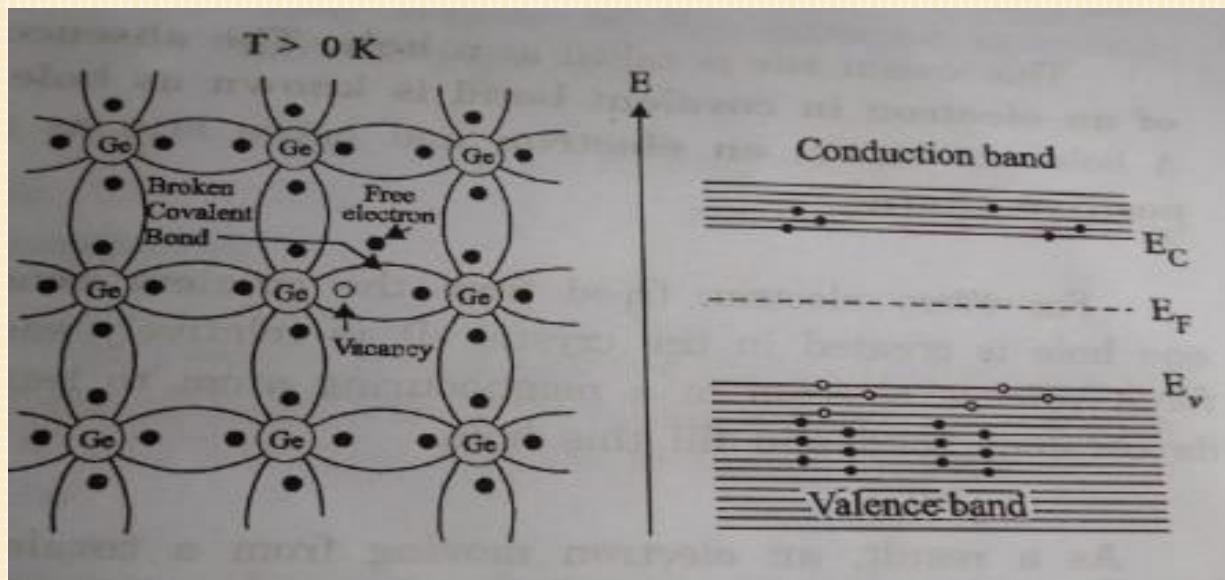


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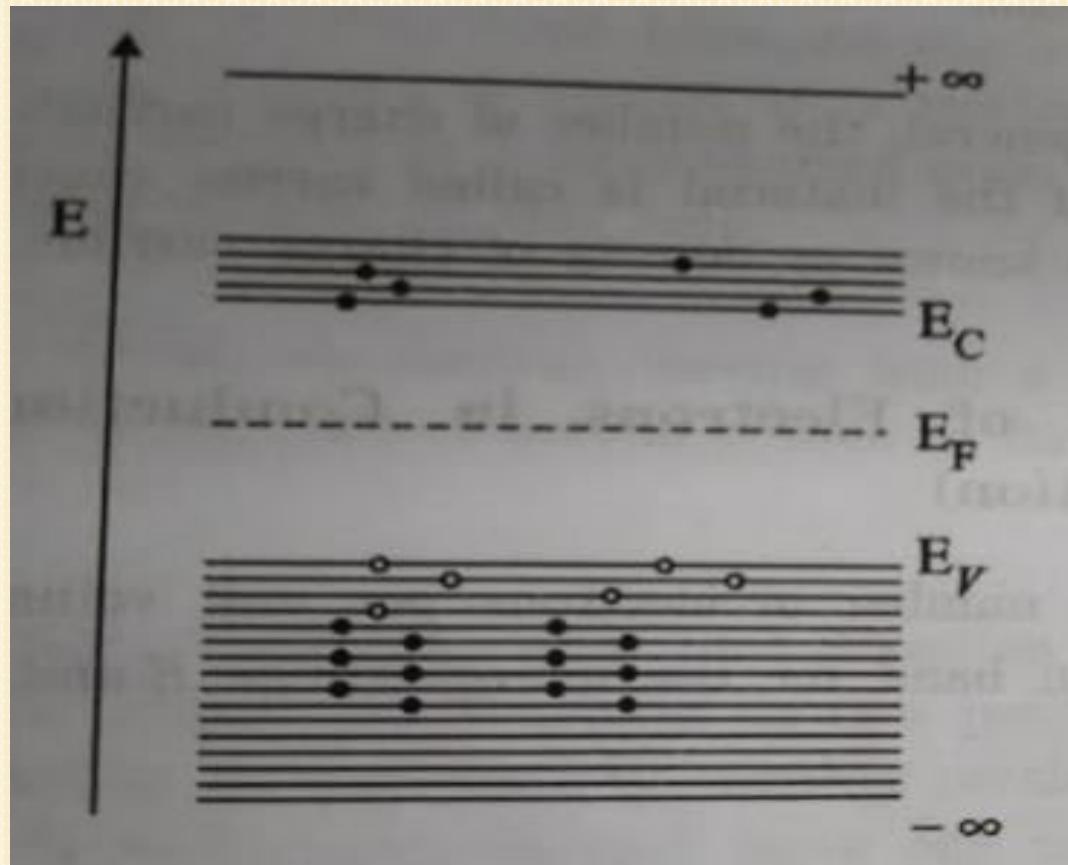


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# Carrier Concentration in an Intrinsic Semiconductor

The number of charge carriers per unit volume of the material is called Carrier concentration (density of charge carriers).



Energy Band Diagram  
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where  $n_i$  is the intrinsic carrier concentration.

$$np = n_i * n_i = n_i^2$$

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Substituting the expressions for n & p we get,

$$n_i^2 = 2 \left( \frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_C)/kT} \times 2 \left( \frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F)/kT}$$

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

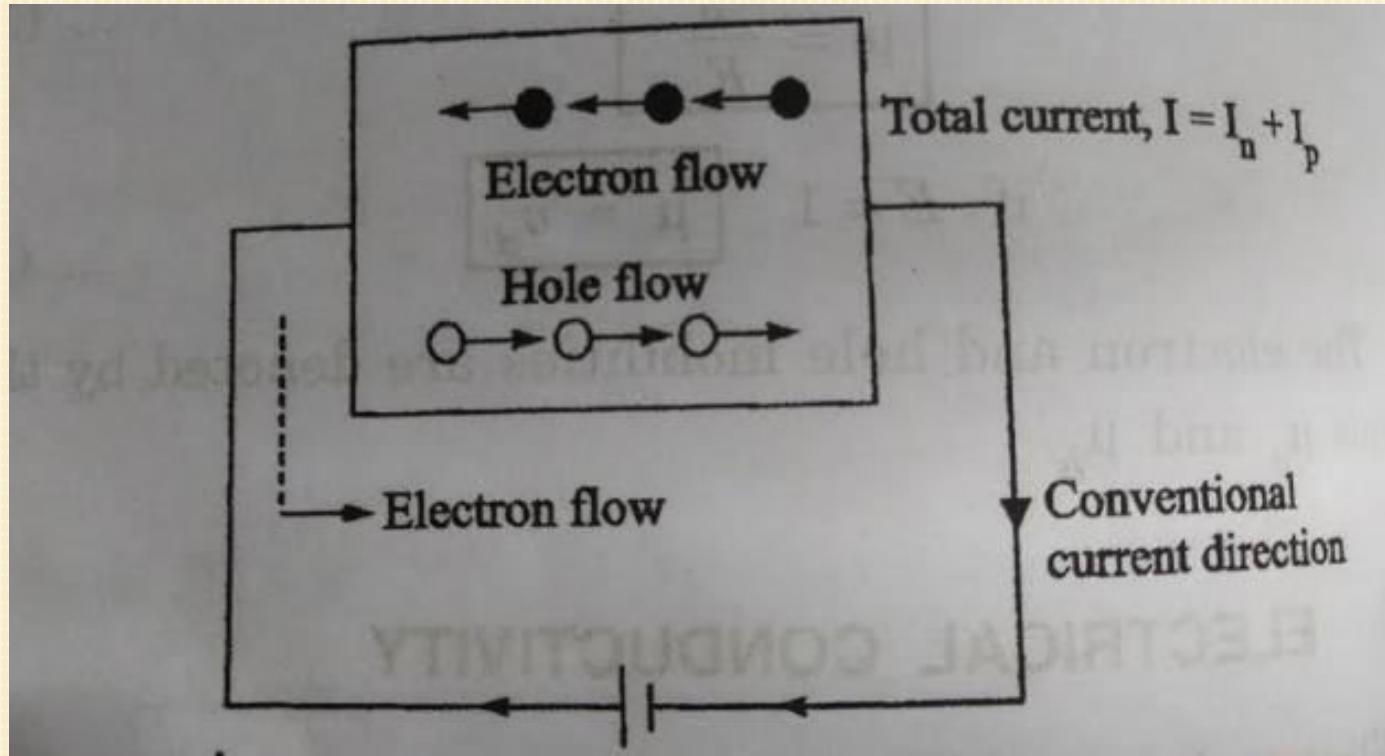
$$n_i^2 = 4 \left( \frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} e^{-E_g/kT}$$

...  
...

where  $E_C - E_v = E_g$  is the forbidden energy gap.

$$n_i = 2 \left( \frac{2\pi kT}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2kT}$$

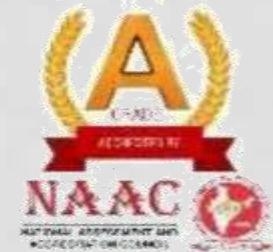
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The charge carriers in a semiconductor are electrons and holes. Both the charge carriers will take part in the current conduction



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## UNIT - III

# SEMICONDUCTOR PHYSICS



**PRESENTED BY**

**DR. C. RATHIKA THAYA KUMARI,**  
**Associate Professor,**  
**Department of Physics**

## OPTICAL PROCESS

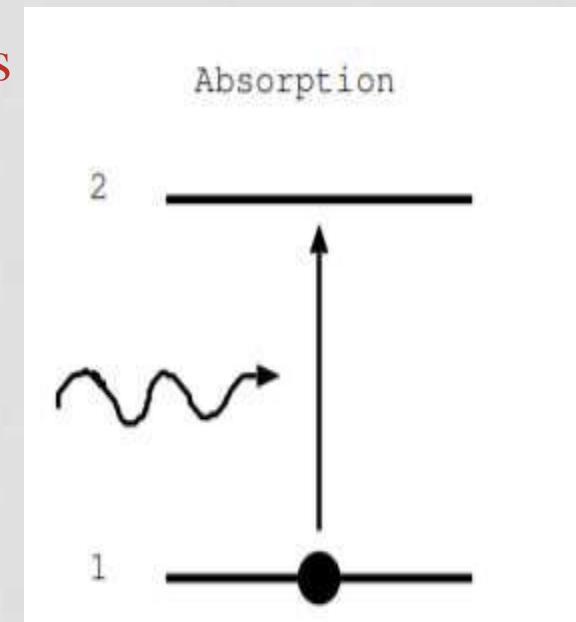
Absorption, spontaneous emission and stimulated emission are three related optical energy conversion processes.

The devices based on absorption are solar cells and photo detectors. Devices which operate based on spontaneous emission include LEDs and lamps. Optical amplifiers and lasers operate based on stimulated emission.

## OPTICAL ABSORPTION

Absorption is the process in which optical energy is converted to internal energy of electrons, atoms, or molecules.

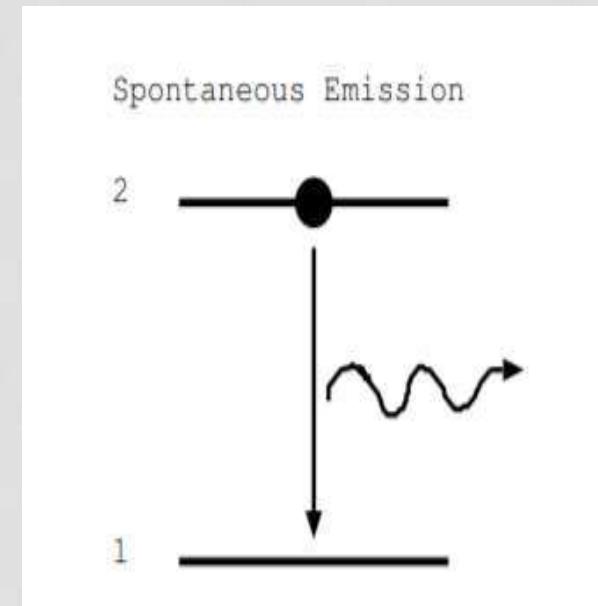
When a photon is absorbed, the energy may cause an electron in an atom to go from a lower to a higher energy level, thereby changing the internal momentum of the electron.



## SPONTANEOUS EMISSION

Spontaneous emission is an energy conversion process in which an excited electron or molecule decays to an available lower energy level and in the process gives off a photon. This process occurs naturally and does not involve interaction of other photons. The average time for decay by spontaneous emission is called the spontaneous emission lifetime.

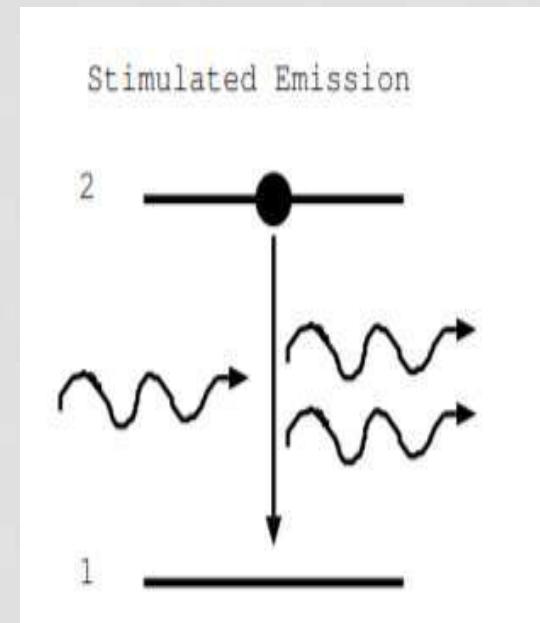
Energy is conserved when the electron decays to the lower level, and that energy must go somewhere. The energy may be converted to heat, mechanical vibrations, or electromagnetic photons. If it is converted to photons, the process is called spontaneous emission



## STIMULATED EMISSION

Stimulated emission is the process in which an excited electron or molecule interacts with a photon, decays to an available lower energy level, and in the process gives off a photon.

If an incoming photon, with energy equal to the difference between allowed energy levels, interacts with an electron in an excited state, stimulated emission can occur.



# RADIATIVE AND NON RADIATIVE TRANSITION

The electron hole pair recombination occurs in two ways:

Radiative transition

Non -Radiative transition

Radiative transitions involve the absorption of a photon, if the transition occurs to a higher energy level or the emission of a photon, for a transition to a lower energy level.

i.e Emission or Absorption of photons.

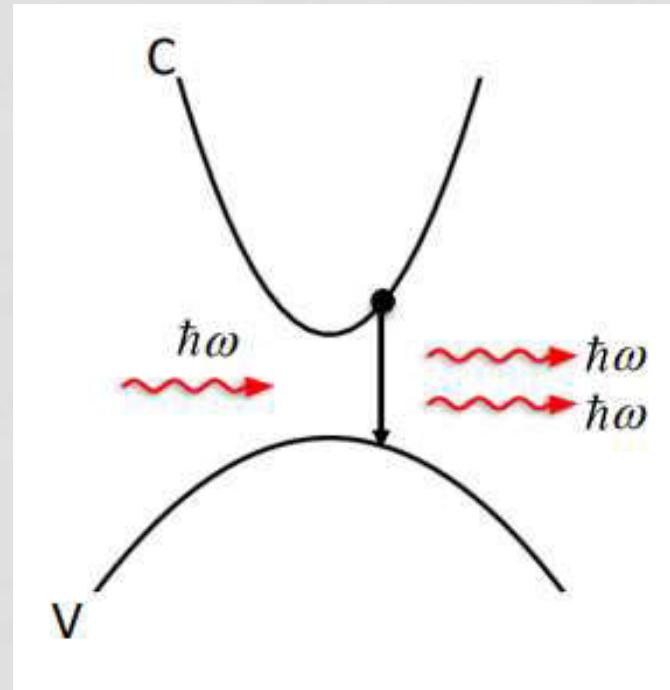
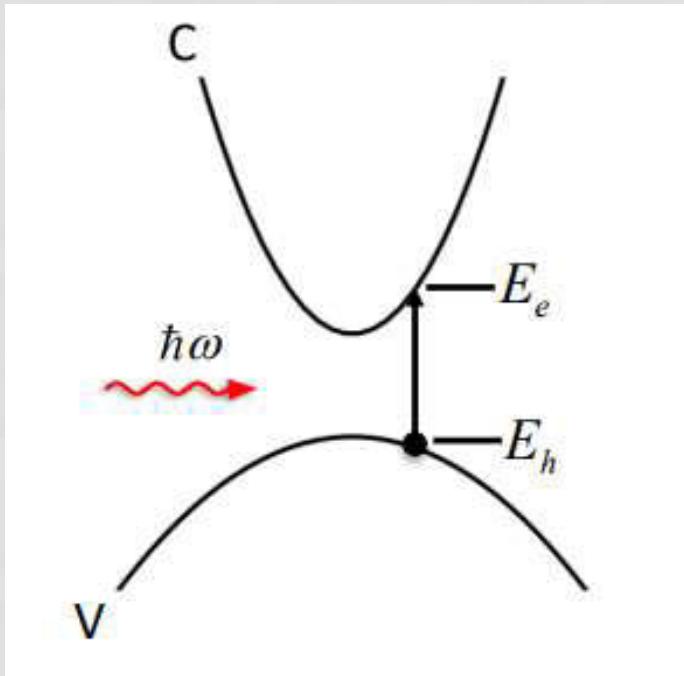
Radiative transition involves Spontaneous and stimulated emission.

During Absorption or emission the energy difference should be  $h\nu$

i.e  $E_1 - E_2 = h\nu$

Thus,  $\Delta K \cong 0$ , because direct emission is possible .

# RADIATIVE TRANSITION

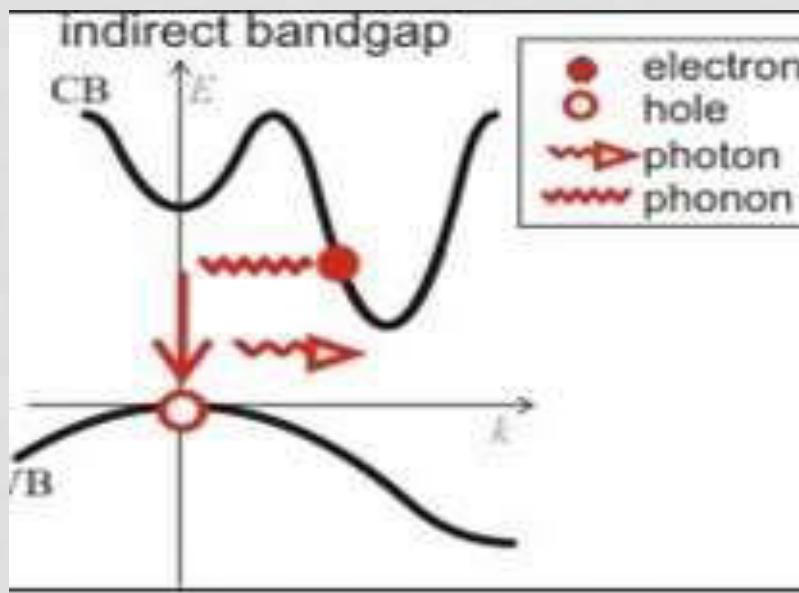


## NON RADIATIVE TRANSITION

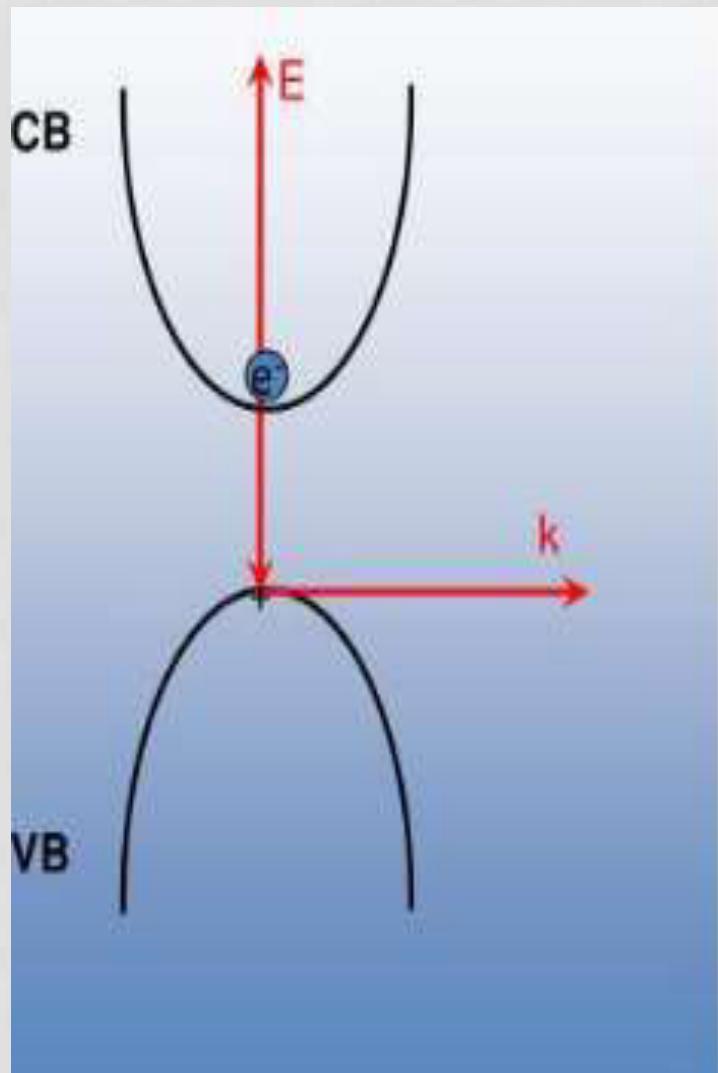
Non radiative transitions between energy levels of atoms or ions which are not associated with the emission of light. This type of transitions does not involve in emission and absorption of photons.

The excess energy is released in the form of heat during electron hole recombination.

This type of transitions occur in indirect band gap materials.



## DIRECT BAND GAP MATERIAL



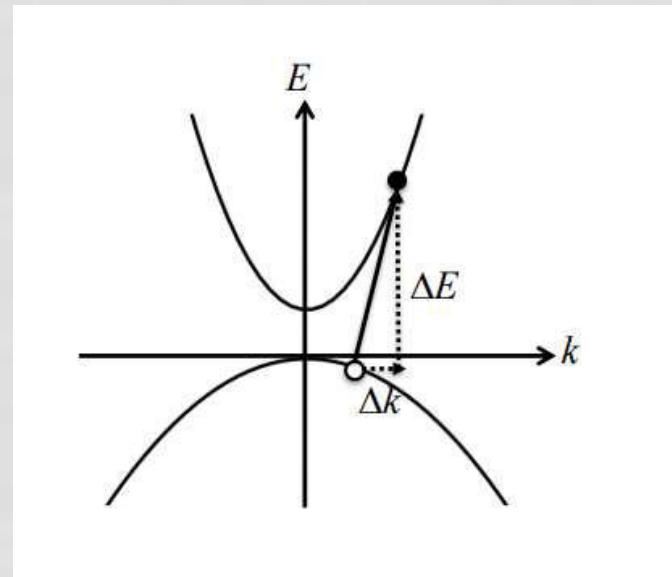
- For a *direct-band gap material*, the minimum of the **conduction band** and maximum of the **valence band** lies at the same momentum,  $k$ , values.
- When an electron sitting at the bottom of the **CB** recombines with a hole sitting at the top of the **VB**, there will be no change in momentum values.
- Energy is conserved by means of emitting a photon, such transitions are called as **radiative transitions**.

## JOINT DENSITY OF STATES

Joint density of states gives the number of pairs of states (one in the valence band and one in the conduction band) per unit volume per unit photon energy interval whose energy difference equal to  $\hbar\nu$ .

This does not depend on actual value of energy levels  $E_1$  and  $E_2$  but depends on the difference of energy levels  $E_1$  and  $E_2$ .

For a single photon, there are number of pairs of  $E_2 - E_1$  of energy  $\hbar\nu$  to interact . Hence at interaction,



## JOINT DENSITY OF STATES

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_c} \quad \text{--- } ①$$

$$E_1 = E_v - \frac{\hbar^2 k^2}{2m_v} \quad \text{--- } ②$$

$$\therefore E_2 - E_1 = (E_c - E_v) + \frac{\hbar^2 k^2}{2} \left[ \frac{1}{m_c} + \frac{1}{m_v} \right]$$

$$h\nu = E_g + \frac{\hbar^2 k^2}{2} \left[ \frac{1}{m_v} \right]$$

$$h\nu = E_g + \frac{\hbar^2 k^2}{2m_v}$$

—

## JOINT DENSITY OF STATES

From this,  $k^2 = (h\nu - Eg) \cdot \frac{2m_r}{\hbar^2}$

ie  $k^2 = \frac{2m_r}{\hbar^2} (h\nu - Eg)$  — ③

Substituting  $k^2$  in eqn (1),

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_c}$$

$$E_2 = E_c + \frac{\hbar^2}{2m_c} \cdot \frac{2m_r}{\hbar^2} (h\nu - Eg)$$

$$E_2 = E_c + \frac{m_r}{m_c} (h\nu - Eg)$$
 — ④

## JOINT DENSITY OF STATES

From eqn (4),

$$E_2 - E_c = \frac{m_r}{m_c} (h\nu - E_g)$$

$$(E_2 - E_c)^{1/2} = \left(\frac{m_r}{m_c}\right)^{1/2} (h\nu - E_g)^{1/2}.$$

Let the density of states for the conduction band is,  $\rho_c(E_2) dE_2$  is equal to joint density of states

$P_\nu d\nu$ .

i.e  $\rho_c(E_2) dE_2 = P(\nu) d\nu$ .

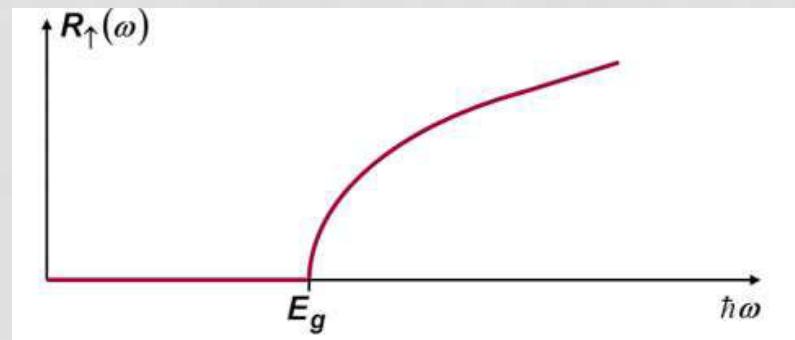
$$\therefore P(\nu) = \rho_c E_2 \cdot \frac{dE_2}{d\nu}$$

## JOINT DENSITY OF STATES

$$\begin{aligned}\therefore \rho(\nu) &= P_c E_2 \cdot \frac{dE_2}{d\nu} \\ &= \frac{1}{2\pi^2} \left( \frac{2m_c}{\hbar^2} \right)^{3/2} (E_2 - E_1)^{1/2} \cdot h \left( \frac{m_r}{m_c} \right) \\ \rho(\nu) &= \frac{1}{\pi\hbar^2} (2m_c)^{3/2} \left( \frac{m_r}{m_c} \right)^{1/2} \left( \frac{m_r}{m_c} \right) (h\nu - Eg)^{1/2} \\ \therefore \rho(\nu) &= \frac{1}{\pi\hbar^2} (2m_r)^{3/2} (h\nu - Eg)^{1/2}.\end{aligned}$$

## JOINT DENSITY OF STATES

When the transition rate is plotted as a function of the photon energy. There are no inter band transitions if the photon energy is smaller than the band gap. The transition rate increases as the joint density of states for photon energies larger than the band gap. The probability of absorption and emission can be determined by considering two cases:



**Case 1:** Under thermal equilibrium, the probability of occupancy in the valence band and conduction band is simultaneously described by one Fermi function. So, under thermal equilibrium the probability of absorption is much more than the probability of emission.

$$P_{\text{abs}} \ggg P_{\text{emi}}$$

## JOINT DENSITY OF STATES

**Case 2:** Under Quasi equilibrium, the probability of occupancy in the valence band and conduction band is simultaneously described by two Fermi function. So, under quasi equilibrium the probability of emission is much more than the probability of absorption.

$$P_{\text{emi}} \ggg P_{\text{abs}}$$

## OPTICAL TRANSITIONS

Consider a semiconductor in which the valence band and conduction band energy levels are given as,

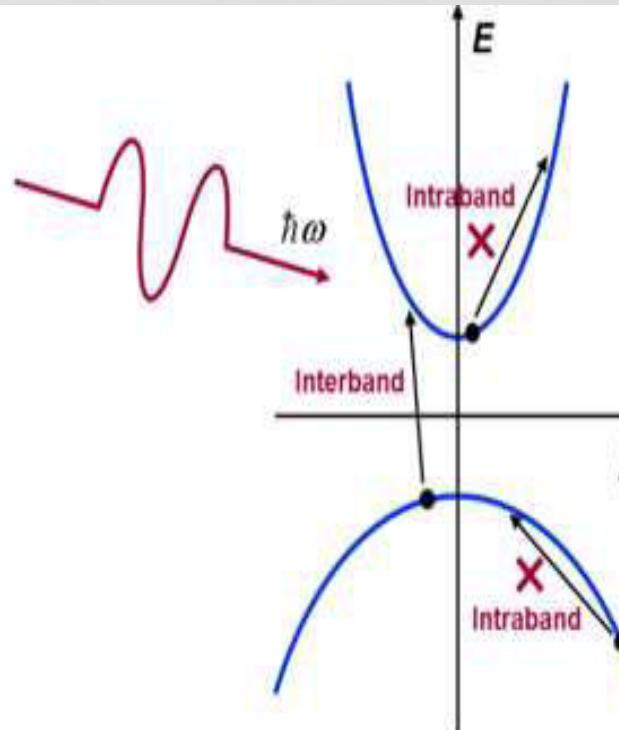
When an electromagnetic wave is propagating through the semiconductor, two kinds of photonic transitions are possible:

- 1. Inter band transition**
- 2. Intra band Transition**

Inter band transition means the electron makes a transition from one band in to another band and Intra band transition means the electron makes a transition in the same band itself.

$$E_c(\vec{k}) = E_c + \frac{\hbar^2 k^2}{2m_e}$$

$$E_v(\vec{k}) = E_v - \frac{\hbar^2 k^2}{2m_h}$$



## FERMI'S GOLDEN RULE

**Fermi's golden rule** is a formula that describes the transition rate .

i.e. the probability of a transition per unit time from one energy eigen state of a quantum system to a group of energy eigen states in a continuous quantum system. This transition rate is effectively independent of time and is proportional to the strength of the interaction between the initial and final states of the system as well as the density of states.

The probability decay rate  $\Gamma$  is given by,

$$\Gamma = \frac{2\pi}{\hbar} \sum_{n \neq k} \left| \langle \phi_n | \hat{H}_- | \phi_k \rangle \right|^2 \delta(\varepsilon_k - \varepsilon_n - \hbar\omega) + \frac{2\pi}{\hbar} \sum_{n \neq k} \left| \langle \phi_n | \hat{H}_+ | \phi_k \rangle \right|^2 \delta(\varepsilon_k - \varepsilon_n + \hbar\omega)$$

The probability decay rate consists of two parts. The first part is due to transitions from the initial state to all final states whose energy is smaller than the energy of the initial state.

## FERMI'S GOLDEN RULE

The second part is due to transitions from the initial state to all final states whose energy is larger than the energy of the initial state.

Fermi's golden rule states that,

- a. Transition rate (or transition probability per second) to states of higher energy is given as,

$$\frac{2\pi}{\hbar} \sum_{n \neq k} \left| \langle \phi_n | \hat{H}_+ | \phi_k \rangle \right|^2 \delta(\varepsilon_k - \varepsilon_n + \hbar\omega)$$

- b. Transition rate to states of lower energy is given as,

$$\frac{2\pi}{\hbar} \sum_{n \neq k} \left| \langle \phi_n | \hat{H}_- | \phi_k \rangle \right|^2 \delta(\varepsilon_k - \varepsilon_n - \hbar\omega)$$

In each case, upward or downward transitions, the final states are those that are connected to initial state by the matrix elements, respectively.

## PHOTO VOLTAIC EFFECT

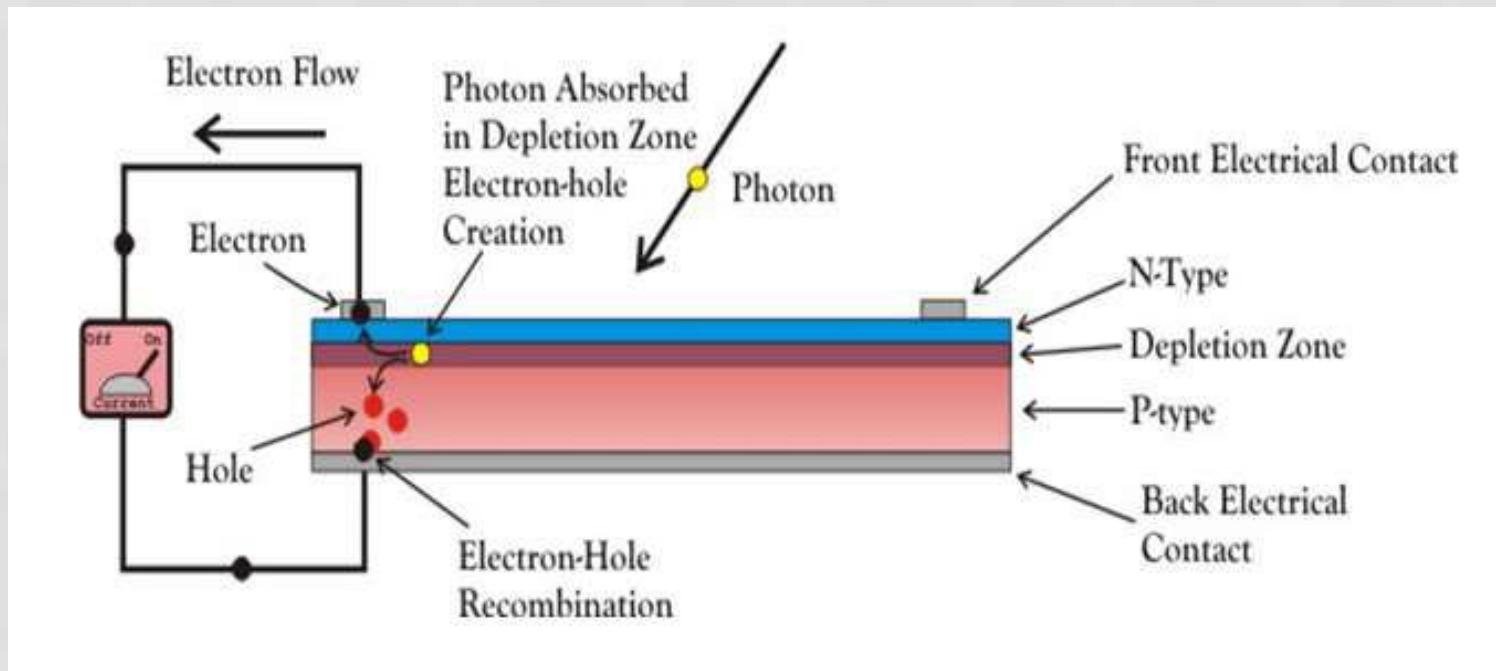
When a voltage is developed across the diode terminals due to light falling on the surface of the diode is known as photo voltaic effect.

A **solar cell** (also known as a photovoltaic cell or PV cell) is defined as an electrical device that converts light energy into electrical energy through the photo voltaic effect. A solar cell is basically a p-n junction diode. Solar cells are a form of photoelectric cell which is defined as a device whose electrical characteristics – such as current, voltage or resistance – vary when exposed to light.

Individual solar cells can be combined to form modules commonly known as solar panels. When combined into a large solar panel, considerable amounts of renewable energy can be generated.

## APPLICATIONS OF PHOTO VOLTAIC EFFECT - SOLAR CELL

solar cell is basically a junction diode, although its construction is different from conventional p-n junction diodes. A very thin layer of p type semiconductor is grown on a relatively thicker n- type semiconductor. We then apply a few finer electrodes on the top of the p-type semiconductor layer.



## CONSTRUCTION OF SOLAR CELL

These electrodes do not obstruct light to reach the thin p-type layer. Just below the p-type layer there is a p-n junction. We also provide a current collecting electrode at the bottom of the n-type layer. We encapsulate the entire assembly by thin glass to protect the **solar cell** from any mechanical shock.

## WORKING OF SOLAR CELL

When light reaches the p-n junction, the light photons can easily enter in the junction, through very thin p-type layer. The light energy, in the form of photons, supplies sufficient energy to the junction to create a number of electron-hole pairs. The incident light breaks the thermal equilibrium condition of the junction. The free electrons in the depletion region can quickly come to the n-type side of the junction.

## WORKING OF SOLAR CELL

Similarly, the holes in the depletion can quickly come to the p-type side of the junction. Once, the newly created free electrons come to the n-type side, cannot further cross the junction because of barrier potential of the junction. Similarly, the newly created holes once come to the p-type side cannot further cross the junction became of same barrier potential of the junction. As the concentration of electrons becomes higher in one side, i.e. n-type side of the junction and concentration of holes becomes more in another side, i.e. the p-type side of the junction, the p-n junction will behave like a small battery cell. A voltage is set up which is known as photo voltage. If we connect a small load across the junction, there will be a tiny current flowing through it.

## EFFICIENCY OF A PV CELL

Solar cells are used as electrical generators to operate water heaters, cookers, electric motors etc. Due to lack of technique to fabricate the high quality junctions with large area, the maximum conversion efficiency of only 15 percent has been achieved in silicon solar cells.

If some radiation other than light , such as heat radiations are used to illuminate the photo diode, it is called the photo detector. A typical photo detector is CdS.

# Concept of Carrier Generation

Consider a Germanium atom,

When a temperature is given to a Ge crystal, the covalent bond breaks, electrons become free and can move inside the crystal freely. These free electrons from the valence band gains thermal energy and goes to the conduction band, leaving a hole in the valence band. In this way, the charge carriers are generated in the Ge crystal. Thus, the process of generating electron hole pairs by exciting an electron from valence band to conduction band is called Carrier Generation.

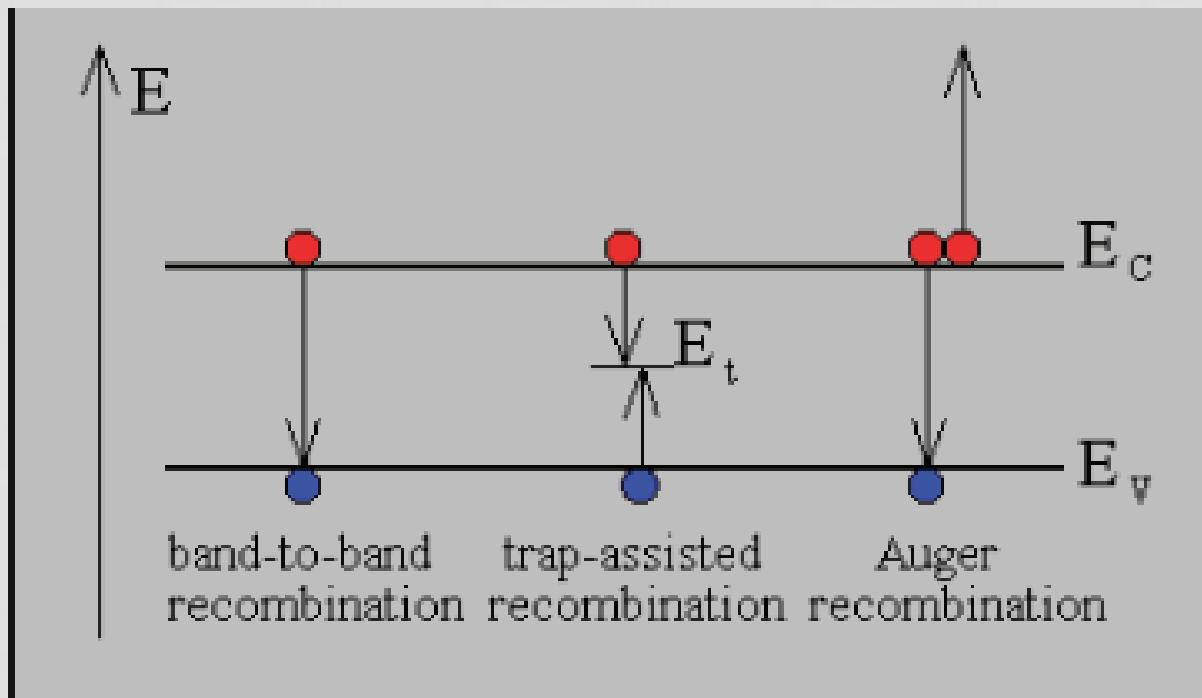
This carriers can be generated by providing heat energy or light energy or electrical energy.

This can be used in light detectors, such as photo detector, pin diode, Avalanche diode, photo diode, Solar cells etc.

# Concept of Carrier Recombination

The Recombination process takes place in three steps as follows:

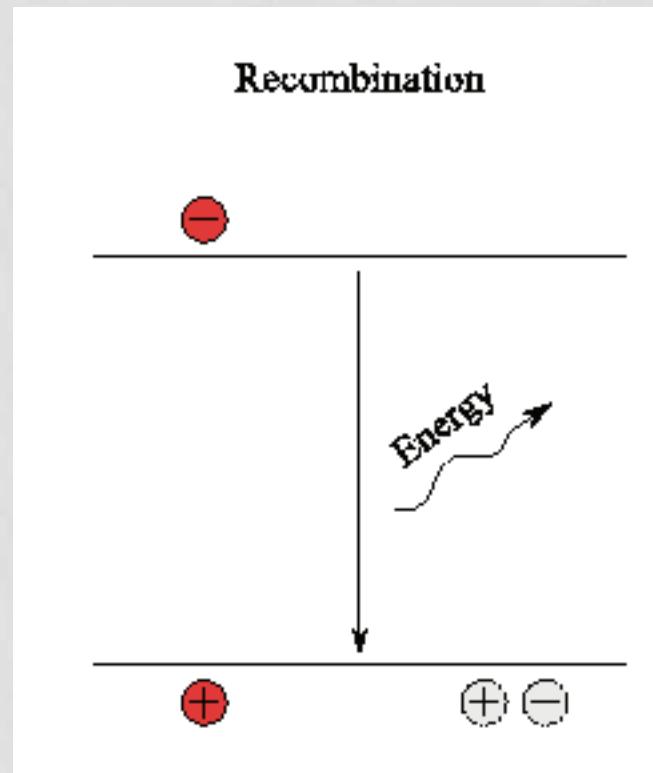
- Band to band recombination or radiative recombination
- Trap assisted or Shockley Read Hall recombination
- Auger recombination



# Band to band Recombination

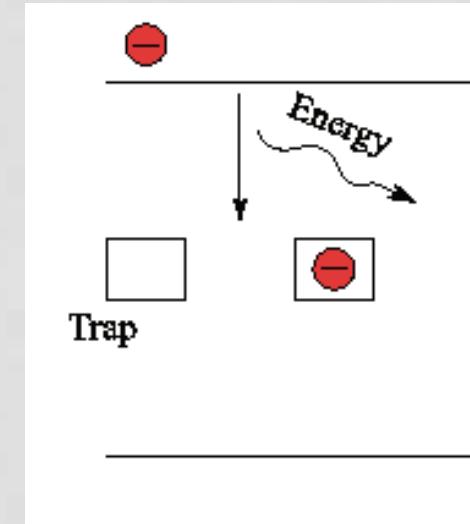
In a band to band recombination, An electron from the conduction band falls back to the valence band and releases its energy in the form of a photon (light).

The photon transition is known as a band-to-band recombination process.

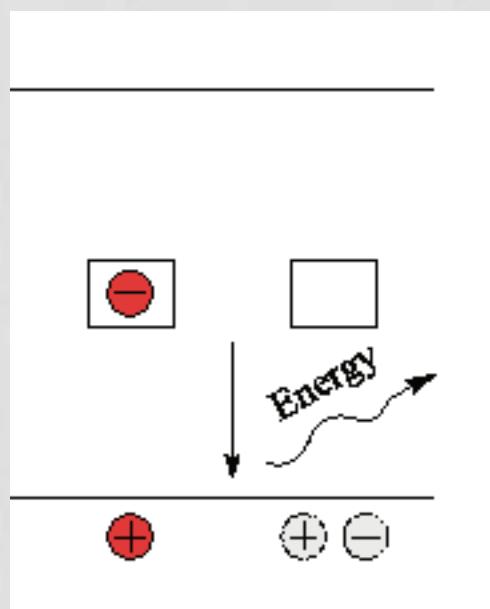


# Trap Assisted Recombination in Semiconductors

An electron from the conduction band is captured by an empty trap in the band-gap of the semiconductor. The excess energy of  $E_c - E_t$  is transferred to the crystal lattice through lattice vibrations (phonon emission).



Electron capture



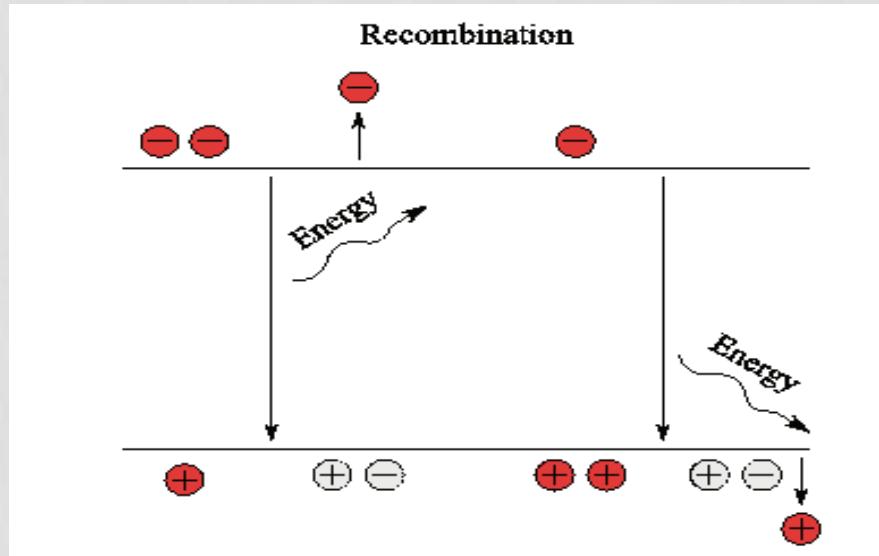
Hole capture

## Hole capture:

The trapped electron moves to the valence band and neutralizes a hole (the hole is captured by the occupied trap). A phonon with the energy  $E_t - E_v$  is generated.

# Auger Recombination

In the Auger recombination three particles are involved. When an electron hole pair recombines, the excess energy is transferred to a third particle.



Auger recombination is a process in which an electron and a hole recombine in a band-to-band transition, but now the resulting energy is given off to another electron or hole. The involvement of a third particle affects the recombination rate so that we need to treat Auger recombination differently from band-to-band recombination.