

Today we will learn about....

Enrico Fermi



Arnold  
Sommerfeld

### **Sommerfeld's Quantum theory metals**

**Fermi** energy, **Fermi** level

**Fermi**-Dirac distribution,

**Fermions**- any particle that obey **Fermi**-

Dirac distribution ..or..too deep into

particle physics!!!...**spin half particles..**

**Eg.. Electron, proton, neutron..**

# Sommerfeld's Quantum theory metals

Arnold **Sommerfeld** who combined the classical **Drude model** with quantum mechanical Fermi–Dirac statistics and hence it is also known as the **Drude–Sommerfeld model**

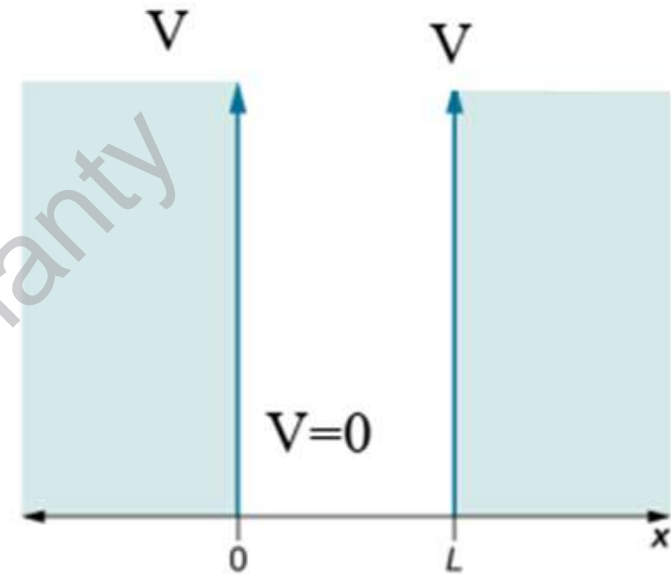
The main assumptions of quantum free electron theory are,

1. The energy levels of the conduction electrons are quantized.
2. The distribution of electrons in various allowed energy levels occur as per Pauli exclusion principle.
3. However, the following assumptions of classical electron theory continue to be applicable in quantum free electron theory also.
  - a) The electrons travel in a constant potential inside the metal but stay confined within its boundaries.
  - b) Both the attraction between the electrons and the lattice ions, and the repulsion between the electrons themselves are ignored.

# Free electron in metal

For simplicity we consider,

- 1) Electron restricted to move in the x-direction only (1 dimensional) from  $x=0$  to  $x=L$
- 2) Potential energy,  $V$  of the electron is 0 inside the metal but rises to infinity outside



$$V = 0 \quad 0 \leq x \leq L$$

$$V = \infty \quad x < 0 \text{ and } x > L$$

This is equivalent to the case where the particle is trapped inside a infinitely deep potential well.. Sommerfeld used Schrödinger equation and applied to electron in metals

## Sommerfeld's Quantum theory metals

$$\nabla^2 \psi + \frac{2mE}{\hbar^2} \psi = 0 \quad \xrightarrow{\text{For 1 D}} \quad \frac{\partial^2 \psi}{\partial x^2} + \frac{2mE}{\hbar^2} \psi = 0 \quad \text{Eq.1}$$

And put  $k^2 = \frac{2mE}{\hbar^2} \quad \text{Eq.2}$

$$\frac{\partial^2 \psi}{\partial x^2} + k^2 \psi = 0 \quad \text{Eq.3}$$

General solution for Eq.3 can be written as

$$\psi(x) = A \sin kx + B \cos kx \quad \text{Eq.4}$$

Where A and B are constant. Now apply the first boundary condition,  $\psi(x)=0$  at  $x=0$

$$\psi(0) = A \sin 0 + B \cos 0 = 0 \quad \longrightarrow \quad B=0$$

$$\psi(x) = A \sin kx \quad \text{Eq.5} \quad \text{Now we will find } k \text{ and } E$$

# Sommerfeld's Quantum theory metals

Now apply the 2<sup>nd</sup> boundary condition.  $\psi(x)=0$  at  $x=L$ . Eq.5 gives

$$\psi(L) = A \sin kL = 0 \quad \Rightarrow \quad \begin{matrix} A \neq 0 \\ \sin kL = 0 \end{matrix} \quad \text{Eq.6}$$

Eq.6 is satisfied only when

$$kL = n\pi \quad \text{Where, } n= 1,2,3$$

$$k = \frac{n\pi}{L}$$

or

$$k^2 = \frac{n^2\pi^2}{L^2} \quad \text{Eq.7}$$

Now substitute Eq.2 in Eq.7

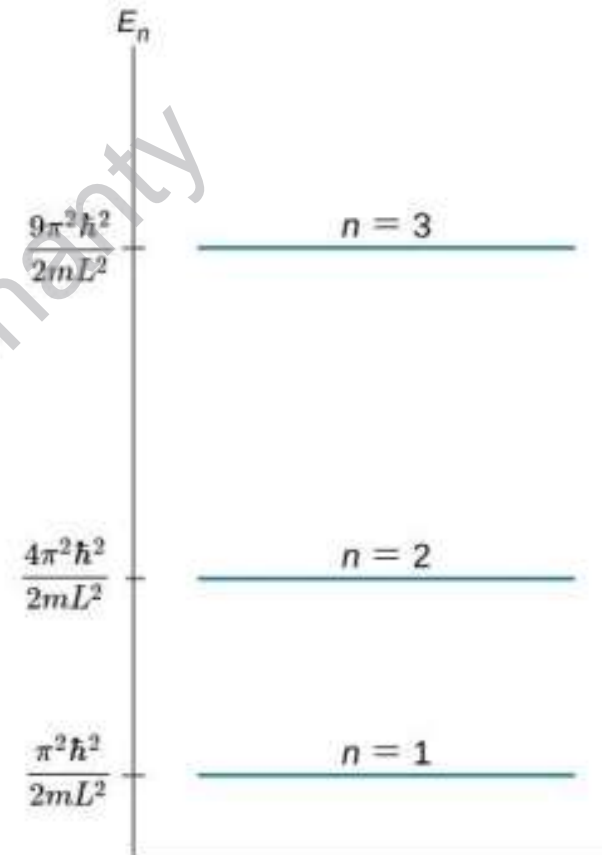
$$k^2 = \frac{2mE}{\hbar^2} = \frac{n^2\pi^2}{L^2} \quad \Rightarrow \quad E = \frac{n^2\hbar^2\pi^2}{2mL^2} \quad \text{Eq.8}$$

Energy of the free electron is discrete and is quantized!!

# Sommerfeld's Quantum theory metals

- $E_n$  Constitute the energy level of the system
- $n$  is the quantum number corresponds to the energy level  $E_n$

$$E_n = \frac{n^2 \hbar^2 \pi^2}{2mL^2}$$

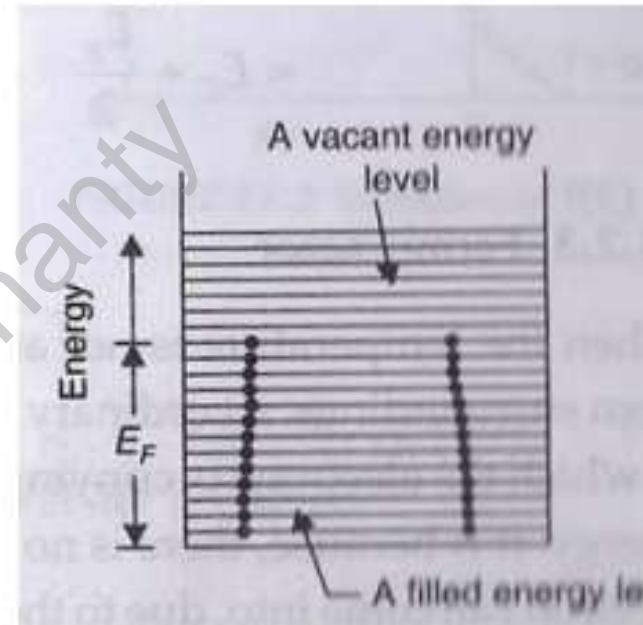


So we found out the energy (**Eigen value**) of the free electron in the metal, with the help of Schrödinger equation



# Sommerfeld's Quantum theory metals

For a metal containing  $N$  free electrons, there will be  $N$  such allowed energy levels, which are separated by energy differences that are characteristic of the material.



The allowed energy values for the conduction electrons in the metal are also quantized, are related to the energy levels of the metal. As per the Pauli exclusion principle, each energy level can accommodate a maximum of two electrons, one with spin up and the other one with spin down

**The energy of the highest occupied level at zero degree absolute temperature is called Fermi energy, and the energy level is referred to as the Fermi level.**

## Fermi-Dirac distribution

*Probability* of finding **an electron** at a particular energy level **E**

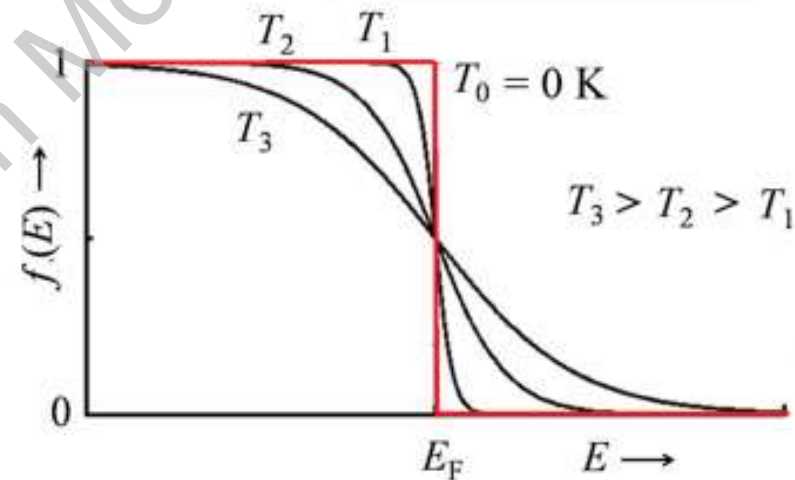
$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

$f(E)$  is the Fermi-Dirac distribution

**Case 1: At absolute zero  $T=0$**

$$\frac{E - E_F}{kT} = \begin{cases} -\infty, & \text{if } E < E_F \\ +\infty, & \text{if } E > E_F \end{cases}$$

$$\therefore f(E) = \begin{cases} 1, & \text{if } E < E_F \\ 0, & \text{if } E > E_F \end{cases}$$



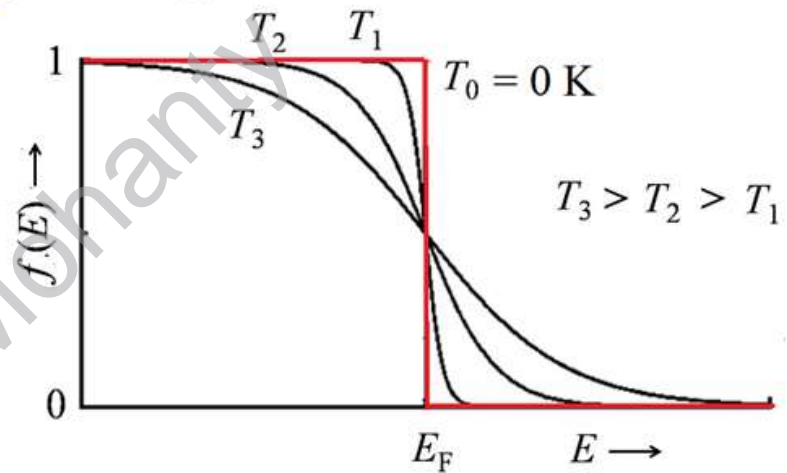
$f(E)$  Follows the red line in figure



## Fermi-Dirac distribution

**Case 2:** At any temperature  $T$  for  $E=E_F$ , the energy level corresponding to  $E=E_F$  is called the Fermi level

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



So the Fermi level is the energy level at which there is half probability of finding an electron. That depends

1. On the number of electrons
2. Distribution of energy levels

low specific heat of metals is now understood

### *Similarities between the two theories*

The following assumptions apply to both the theories:

1. The valence electrons are treated as though they constitute an ideal gas.
2. The valence *electrons* can move freely throughout the body of the solid.
3. The *mutual* repulsion between the electrons, and the force of attraction between the *electrons* and ions are considered insignificant.

Difference between the two theories

#### **Classical Free Electron Theory**

1. The free electrons, which constitute the electron gas can have continuous energy values.
1. It is possible that many electron may possess same energy.
1. The pattern of distribution of energy among the free electron obey Maxwell-Boltzmann statistics.

#### **Quantum Free Electron Theory**

1. The energy values of the free electrons are discontinuous because of which the energy levels are discrete.
1. The free-electrons obey the Pauli exclusion principle. Hence no two electrons can possess same energy.
1. The distribution of energy among the free electrons is according to Fermi Dirac statistics which imposes a severe restriction on the possible way in which the electrons absorb energy from an external source.

## MERITS OF QUANTUM FREE ELECTRON THEORY

- 1) Changed the concept of free electron or conduction electrons in metals
- 2) Successfully explained thermal and electrical conductivity of metals
- 3) Thermionic emission from metals explained
- 4) Temperature dependence conductivity explained
- 5) The theory explained experimentally observed electronic specific heat of metals
- 6) Explained paramagnetic susceptibility

### But failed to Explain

Ferromagnetism in metals

Why some materials are Metal, insulator and semiconductors?

This all are explained at the third stage of development “ **Band theory of solid**’ developed by Bloch, Kroning-Penney etc.. And that will be learned from today onwards

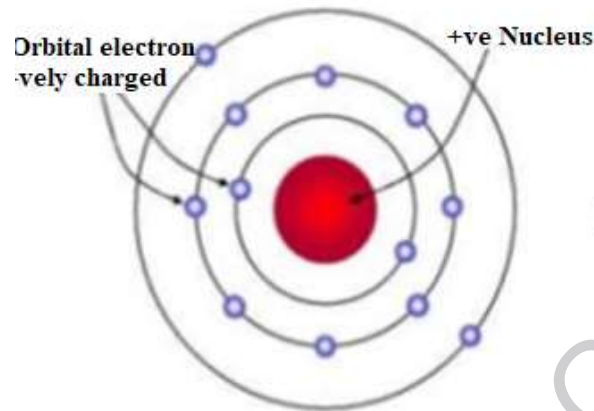
## Today we are going to learn about the band theory of solids

- 1) Electron-ion interaction
- 2) Periodic potential function
- 3) Schrödinger wave equations- for electron in a periodic potential
- 4) Bloch function- solution of Schrödinger wave equation in a periodic potential- Bloch electrons
- 5) Kronig - Penning model- simplification of the periodic potential
- 6) E-k diagram- deviation from the parabolic behavior
- 7) Splitting energy levels- formation of band
- 8) Allowed and forbidden energy – concept of band gap and band overlap



## STAGE 3: Band Theory of Solid

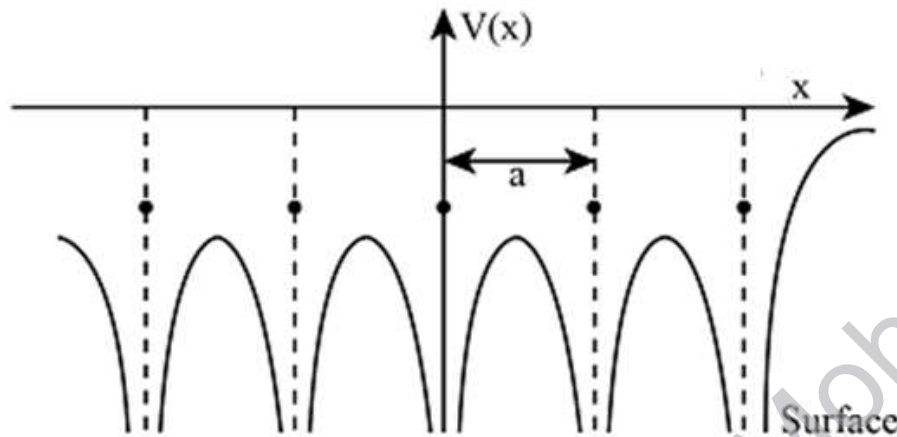
We continue to treat valence electrons as independent (by neglecting  $e^-e^-$  interaction like in stage 1 and stage 2 ) but now we consider the electron-ion interaction. *Solid is a periodic arrangement of atoms....*



1. Free electron: Potential energy,  $V=0$ : Total energy is just the kinetic energy of the electron  
✓ This is the case for electron experience between the ions position in the lattice..
2. Not free when  $V=V_0$ ; when electron is not in the well but at the barrier region, interaction with ion in the lattice considered.  
✓ This is what electron experience at the lattice point
3. So electron wave experience a **periodicity in the potential** as it move through the lattice. ..This bring Bloch function instead Schrödinger wave function



## Electrons in a periodic potential



Quantum mechanical view of the potential (V) experienced by an electron in passing through a crystalline materials

Now we go back to the Schrödinger wave equation we learned in Unit 4 for the electron of mass **m** and energy **E**

For 3D  $\Rightarrow \nabla^2 \psi + \frac{2m}{\hbar^2} (E - V_0) \psi = 0$

For 1 D  $\Rightarrow \frac{\partial^2 \psi}{\partial x^2} + \frac{2m}{\hbar^2} (E - V_0) \psi = 0$  Eqn.1

Solution for Equation 1,  $\psi$ , we have already seen and the also for the  $E - V_0$

$$\psi(x) = e^{\pm ikx} \quad \text{Eqn.2}$$

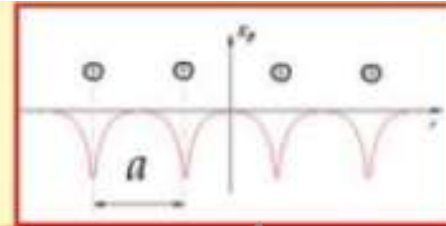
$$E - V = \frac{\hbar^2 k^2}{2m} = \frac{p^2}{2m} = E_k \quad \text{Eqn.3}$$

If the electron is moving through the periodic lattice, it experiences the periodic potential  $V(x) = V(x + a)$  Eqn.4

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{2m}{\hbar^2} [E - V(x)] \psi = 0 \quad \text{Eqn.5}$$

Solution of equation 5 is given by Bloch theory...That is why so the called Bloch's theory of energy band in solids

## Bloch Wavefunctions



- Bloch's Theorem states that for a particle moving in the periodic potential, the wavefunctions  $\psi(x)$  are of the form

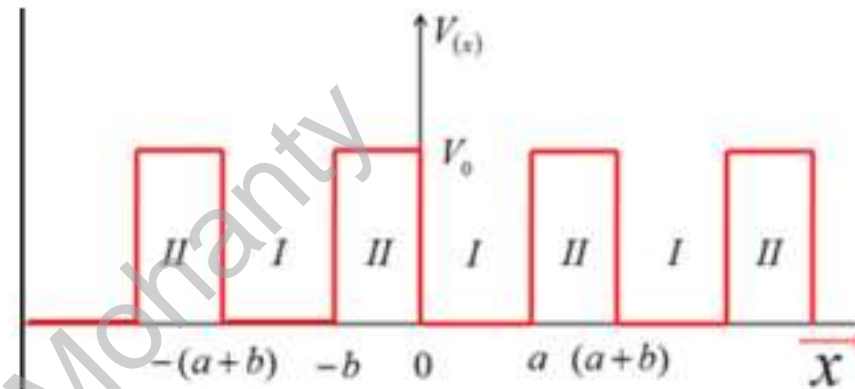
$\psi(x) = u_k(x)e^{\pm ikx}$ , where  $u_k(x)$  is a periodic function

$$u_k(x) = u_k(x + a)$$

- $u_k(x)$  has the periodicity of the atomic potential
  - The exact form of  $u(x)$  depends on the potential associated with atoms (ions) that form the solid

## Kronig-Penney Model for the periodic potential

Simplified the problem by considering square well potential



At the bottom of the well ( $0 < x < a$ )  $V$  is zero and electron is close to the nucleus

Out side of the well ( $-b < x < 0$ ) potential  $V$  is  $V_0$ , electron is away from the nucleus

Schrodinger equations for these two cases can be written as

$$\text{Region 1} \quad \frac{\partial^2 \psi}{\partial x^2} + \frac{2m}{\hbar^2} E \psi = 0 \quad \text{for } (0 < x < a)$$

$$\text{Region 1} \quad \frac{\partial^2 \psi}{\partial x^2} + \frac{2m}{\hbar^2} [E - V_0] \psi = 0 \quad \text{for } (-b < x < 0)$$

If we solve these two equations for **wave function of the Bloch electron** and **energy of the Bloch electron**, we are in the process getting all the answers



In order to find out the allowed energy values of electron while moving in the lattice of periodic potentials due to the bound ionic centers Kroning and penney assumed..

- a) The energy of the electron is less than  $V_0$
- b) Solution of the above equation is Bloch function
- c) Wave function and its derivative are continuous through out the crystal lattice
- d) Product of the width and height of the potential is finite

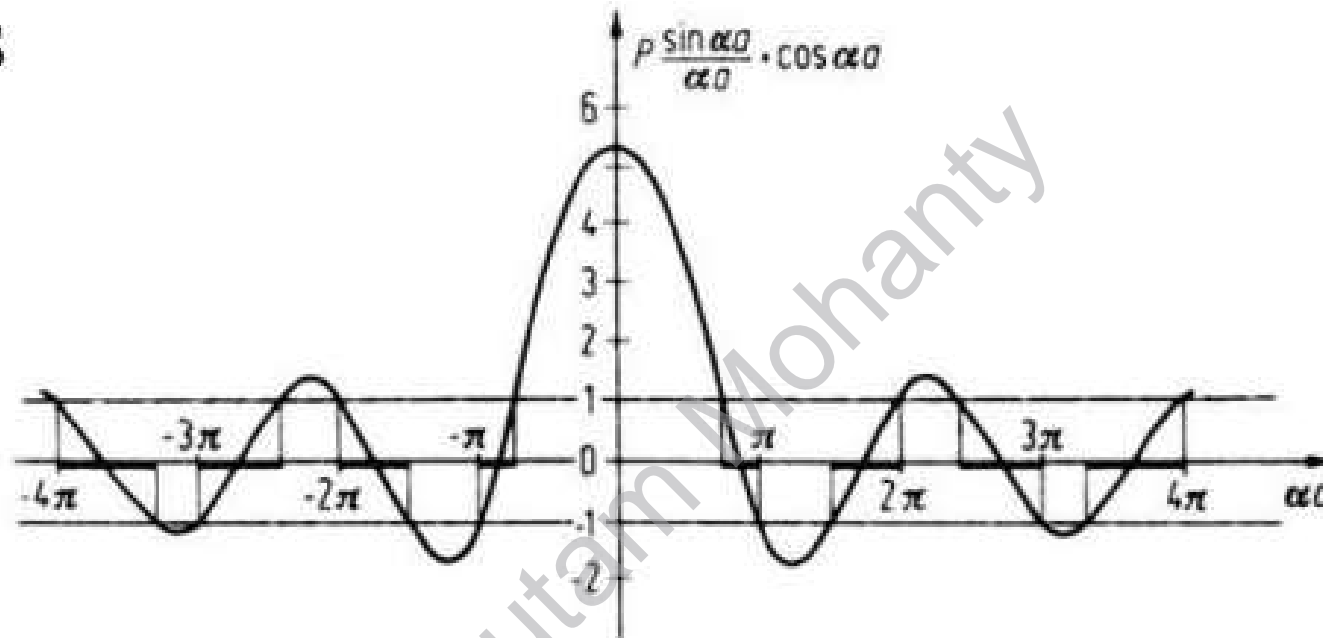
With rigorous mathematical step they obtained the solution for Eq.5 as

$$P \frac{\sin \alpha a}{\alpha a} + \cos \alpha a = \cos Ka \quad \text{Eqn.6}$$

$$P = \frac{maV_0b}{\hbar^2} \quad \text{Eqn.7}$$

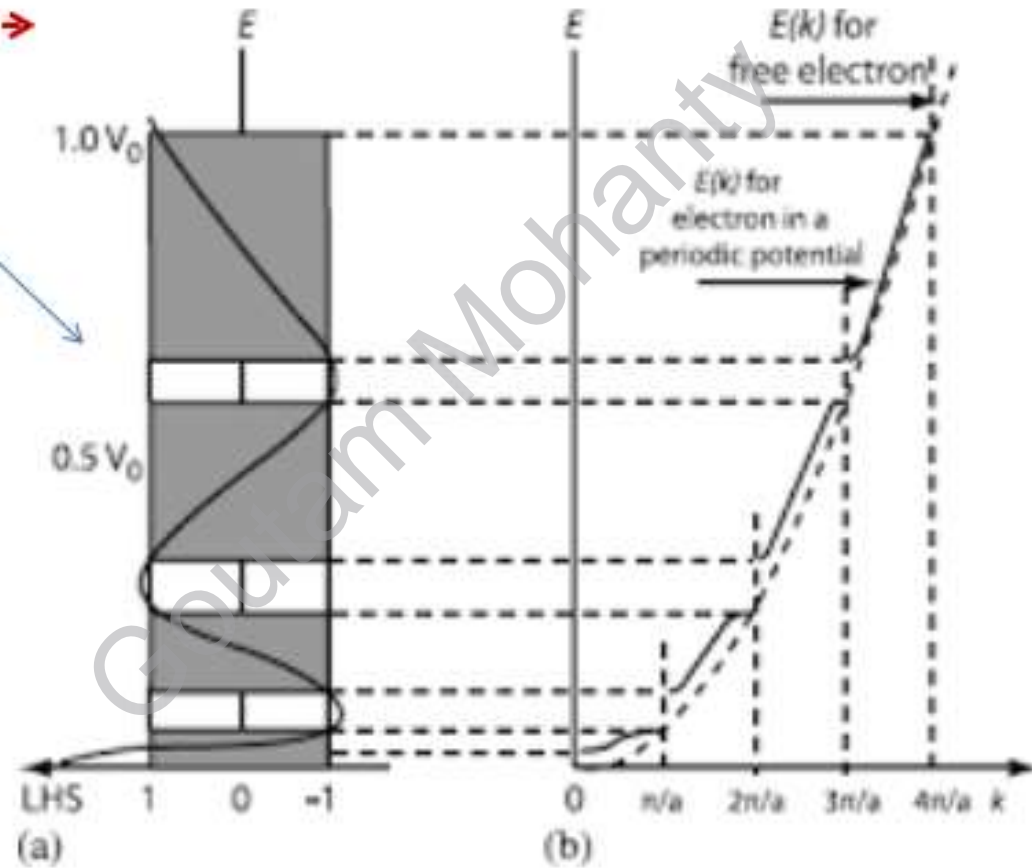
$$\alpha^2 = \frac{2mE}{\hbar^2} \quad \text{Eqn.8}$$

LHS



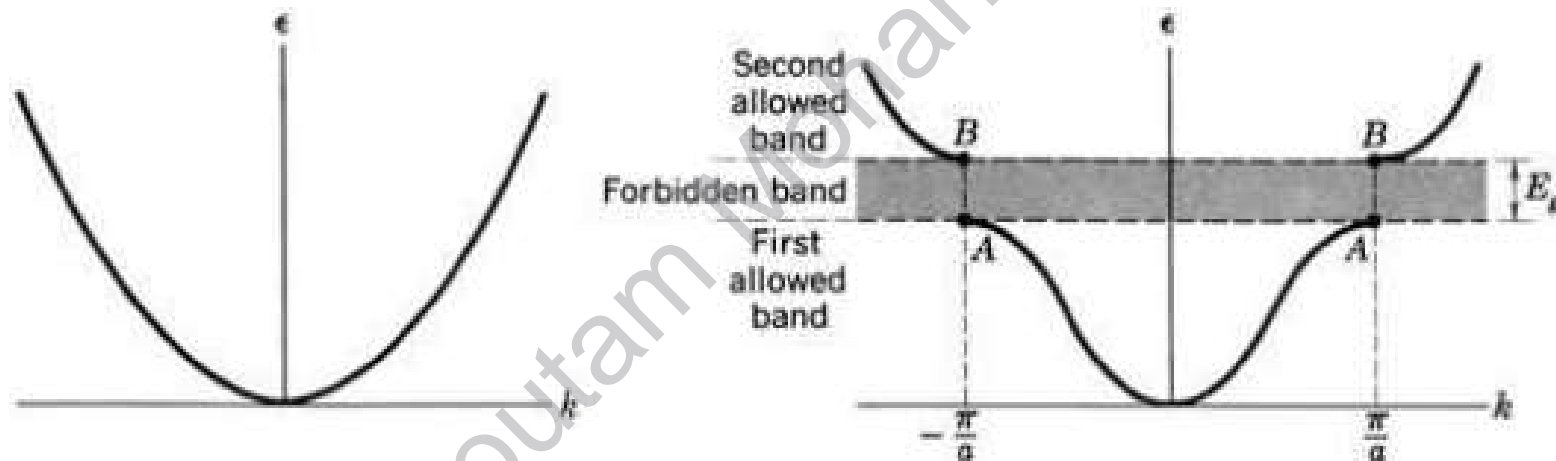
Allowed values of the quantity on the y axis is within  $\pm 1$ , that restrict the energy values allowed for the Bloch electrons..

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



$$E - V = \frac{\hbar^2 k^2}{2m} = \frac{p^2}{2m} = E_k$$

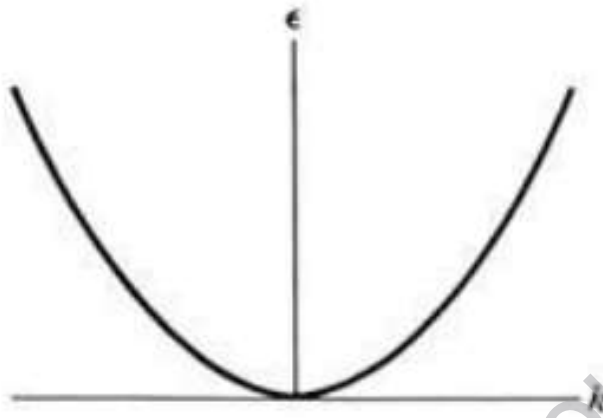
$$E = \frac{\alpha^2 \hbar^2}{2m}$$



So periodic potential modulate the energy of the electron; it restrict it having a band of values and some energy is not allowed to possess in the lattice. **Origin of band gap in material come to exist...** now we can distinguish metal, insulator and semiconductor

## Kinetic energy of electron

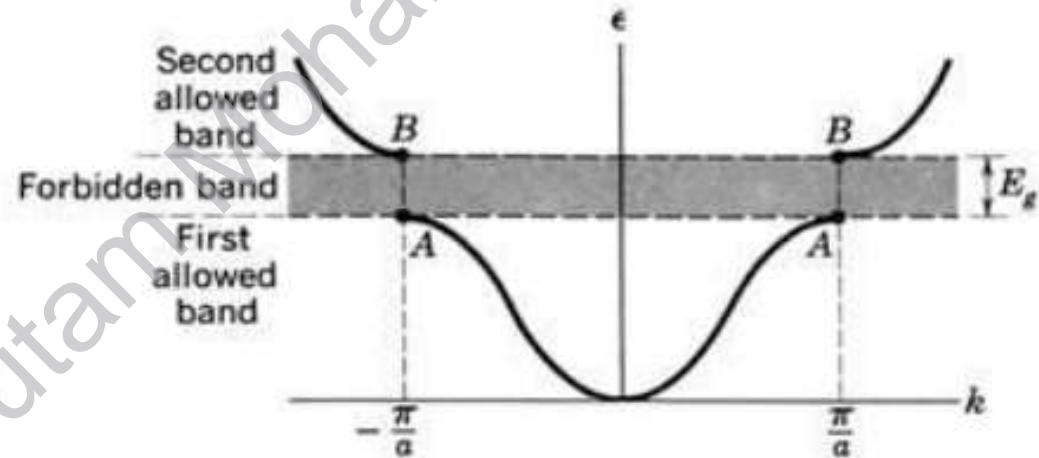
$$E - V = \frac{\hbar^2 k^2}{2m} = \frac{p^2}{2m} = E_k$$



## Quantum free electron theory

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

$$k^2 \rightarrow \alpha^2 = \frac{2mE}{\hbar^2}$$



## Quantum nearly free electron theory

### Electron-lattice interaction

In fact the periodicity of the potential function is responsible for the gap



Today we will learn about

## 1. Classification of solids with band theory concept

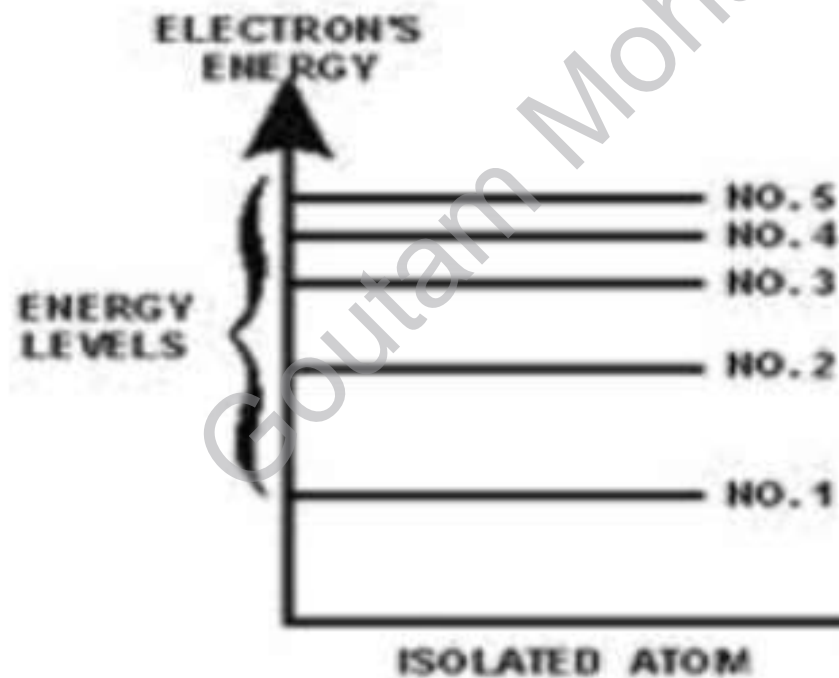
- ☐ Splitting of energy levels: **FORMATION OF A BAND**
- ☐ Merging of bands: **BAND OVERLAP**
- ☐ Valance and conduction bands; **BAND GAP**
- ☐ Conductors (Metals), Semiconductors and Insulators

## 2. Semiconductors

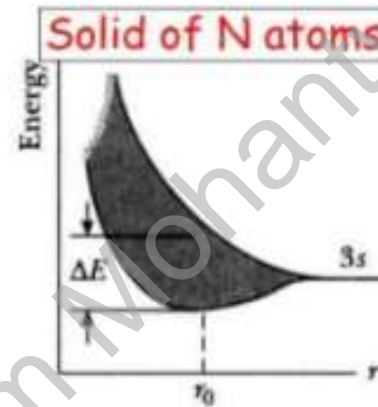
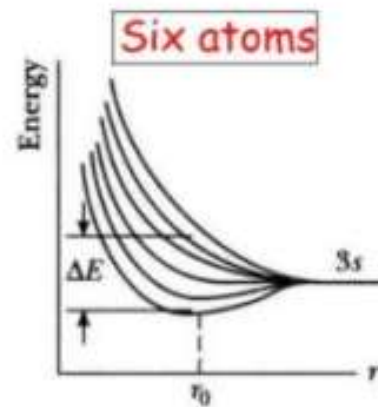
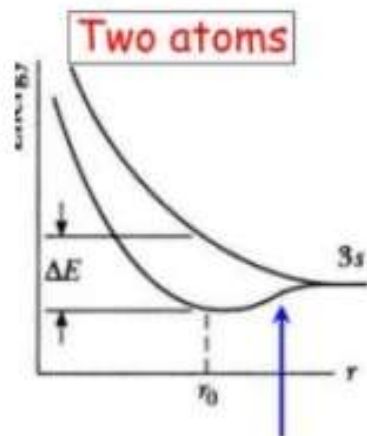
- ☐ Intrinsic and extrinsic semiconductors
- ☐ Fermi level for intrinsic and extrinsic semiconductor,

## ENERGY BANDS IN SOLIDS

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



# Formation of Bands in Solids

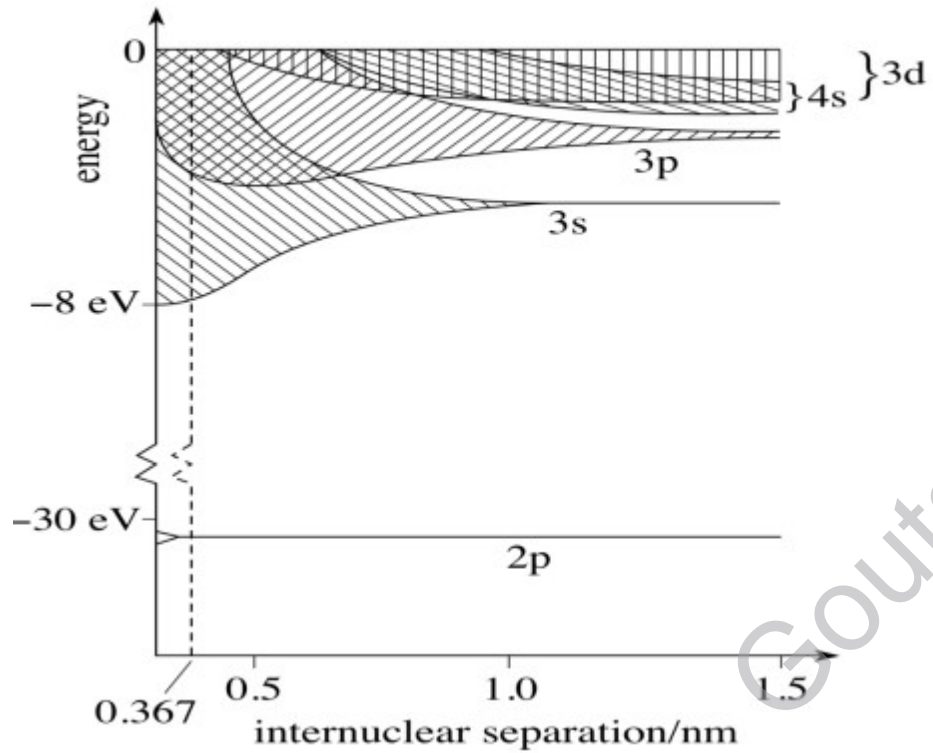


- ✓  $r_0$  is the inter-atomic distance
- ✓ Electrons with identical quantum numbers (1s, share the same band and 2s, 2p etc..) ..like you all are in the same class☺

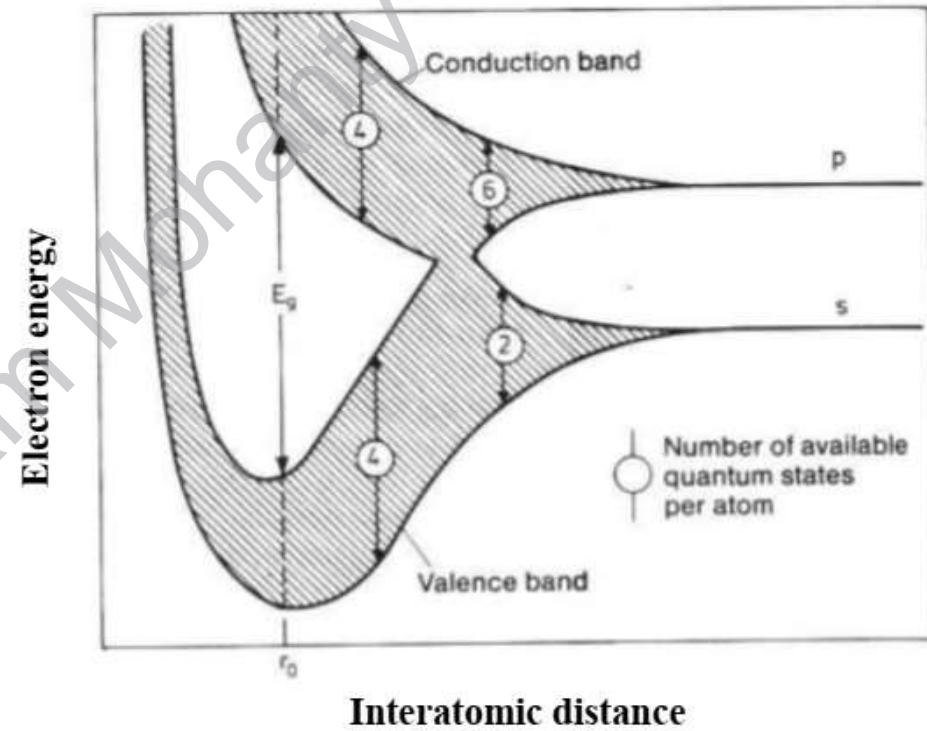
Splitting of discrete energy levels as two atoms come close to form solid due to Pauli's exclusion principle.

All discrete energy levels opens up.. But width  $\Delta E$  increases towards higher levels (quantum numbers, or K,L,M,N etc.. Or s,p,d,f)

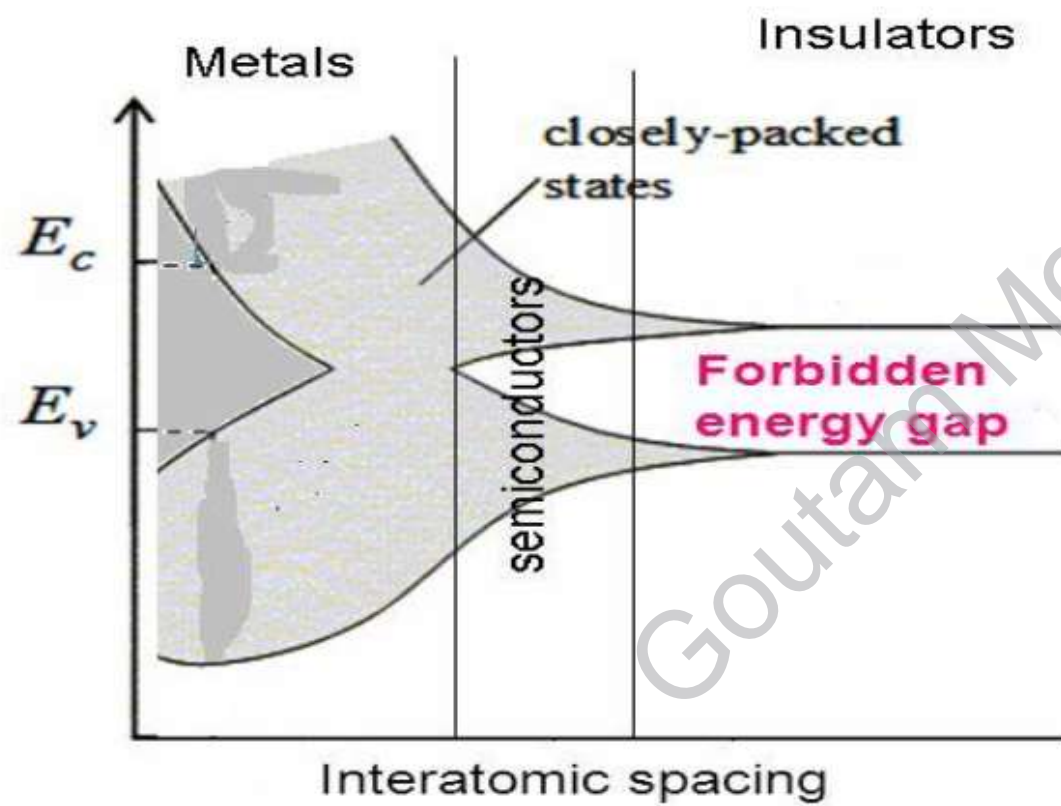
## Merging of bands



## Formation of Band Gap



Insulator or semiconductor





## Insulators

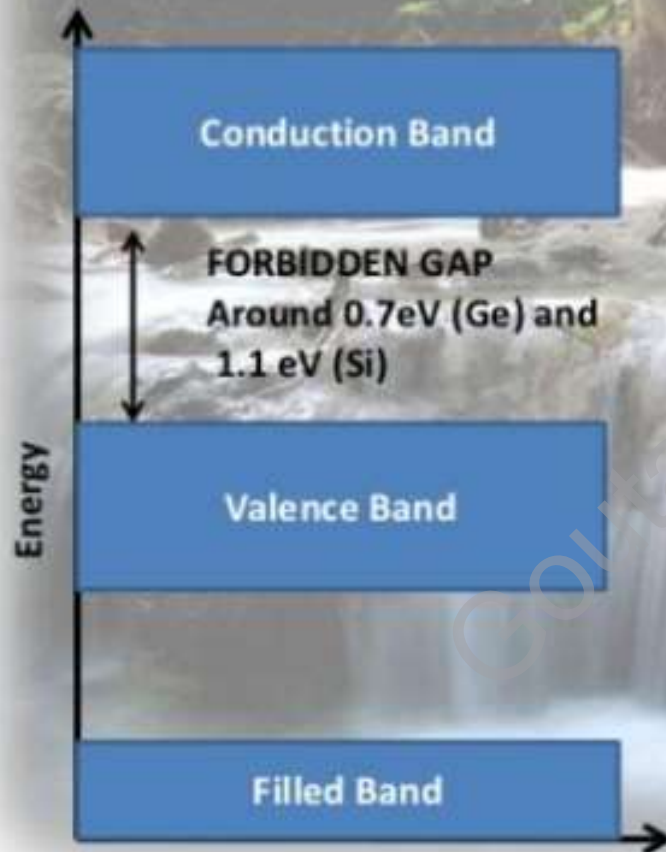


In an insulator, the forbidden gap is very large and in general is more than  $3\text{eV}$ .

No electron is available for conduction.

Large amount of energy is needed to move electron from valance band to conduction band.

# Semiconductors



In the case of semiconductors the forbidden gap is very small.

At 0K the conduction band is empty and the valence band is completely filled.

When a small amount of energy is supplied, the electrons can easily jump the forbidden gap.

The conductivity of a semiconductor is of the order of  $10^{-2} \text{ mho m}^{-1}$

## Conductors

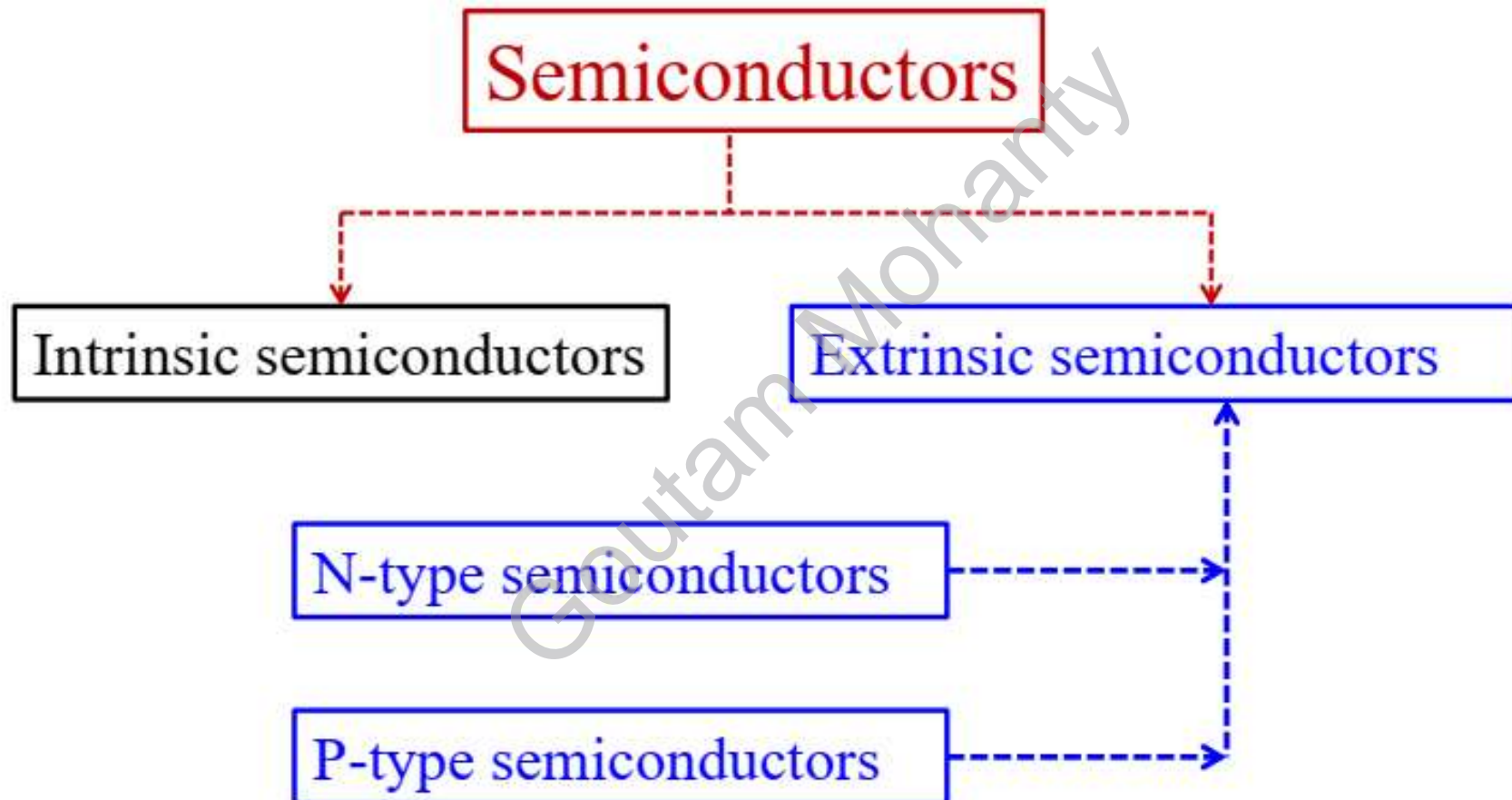


In conductors there is no forbidden gap.

The valence band and the conduction band overlap.

The electrons from valence band freely enter into the conduction band due to overlapping of bands.

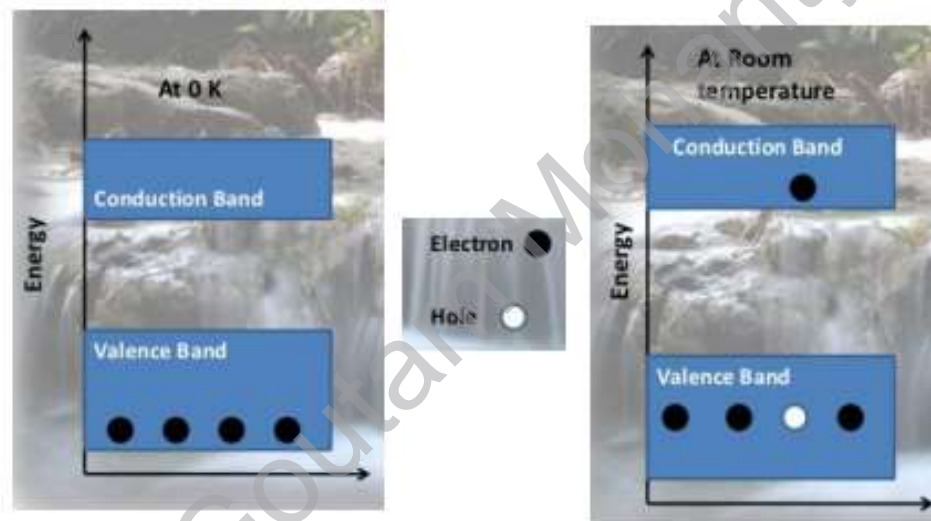
Therefore very low potential difference can cause continuous flow of current.





# Intrinsic semiconductors

In a semiconductor ejection of electron to the conduction band from the valance band is purely by thermal excitation is an intrinsic semiconductor



- The effect is temperature dependent
- Produce equal number of holes and electrons
- Electrons or holes are the intrinsic carriers
- Conductivity is then called the intrinsic conductivity



# Intrinsic semiconductors

Concentration of electron (with effective mass  $m_e$ ) in an intrinsic semiconductor is given by

$$n_e = 2 \left[ \frac{2\pi m_e kT}{h^2} \right]^{3/2} e^{(E_F - E_c)/kT} \quad \text{Eq.1} \quad n_e = n$$

Concentration of holes (with effective mass  $m_h$ ) in an intrinsic semiconductor is given by

$$n_h = 2 \left[ \frac{2\pi m_h kT}{h^2} \right]^{3/2} e^{(E_v - E_F)/kT} \quad \text{Eq.1} \quad n_h = p$$

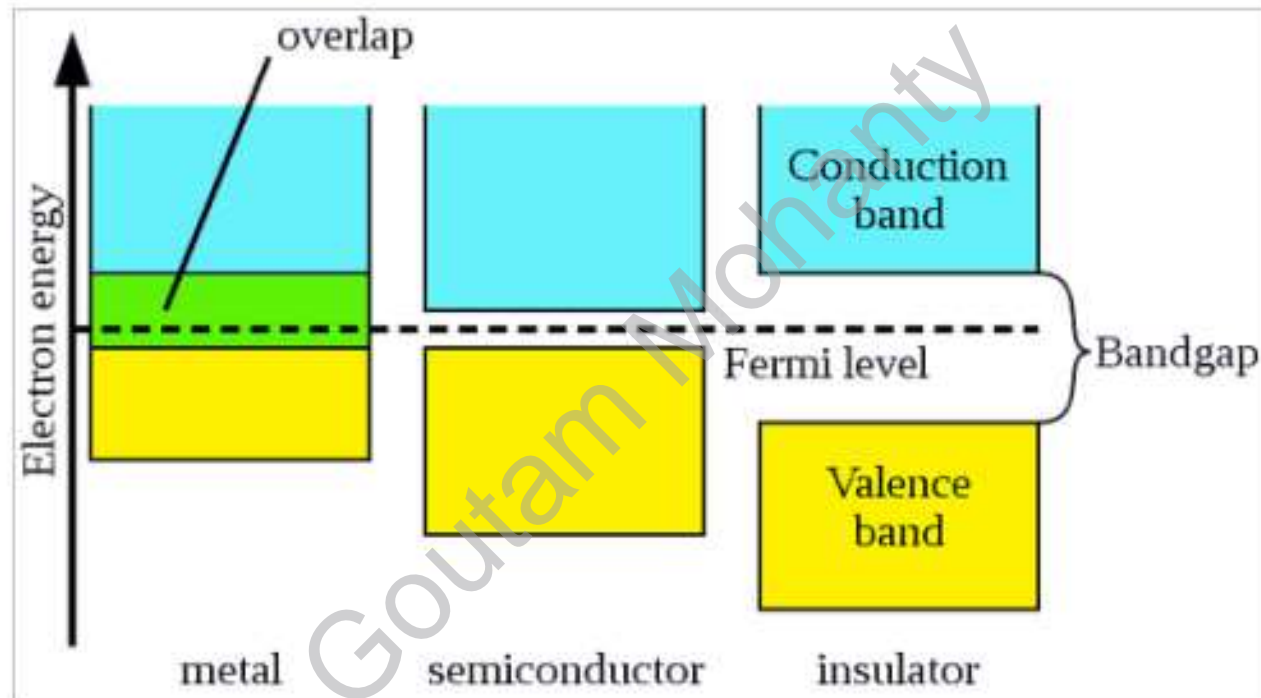
And the product of the two carriers concentration is  $n_e n_h = AT^3 e^{(E_v - E_c)/kT}$  ; a constant for given material and a given temperature

For an intrinsic semiconductor  $n=p=n_i$

$$np = n_i^2 = AT^3 e^{(E_v - E_c)/kT}$$

Very important relation called law of action  
Hold good for extrinsic semiconductors as well

## Fermi level for semiconductor



We defined the Fermi level of a metal as the energy of the top most filled level at absolute zero. Or the Energy of the electron for which probability of finding an electron at any temperature is half at Fermi level.

## Fermi level of intrinsic semiconductor

$$n_e = 2 \left[ \frac{2\pi m_e kT}{h^2} \right]^{3/2} e^{(E_F - E_c)/kT} \qquad n_h = 2 \left[ \frac{2\pi m_h kT}{h^2} \right]^{3/2} e^{(E_v - E_F)/kT}$$

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

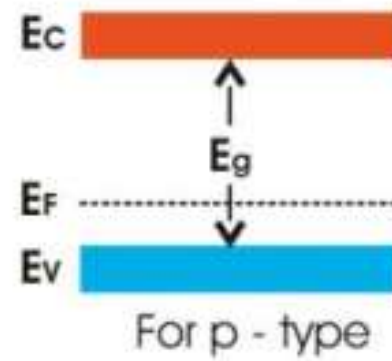
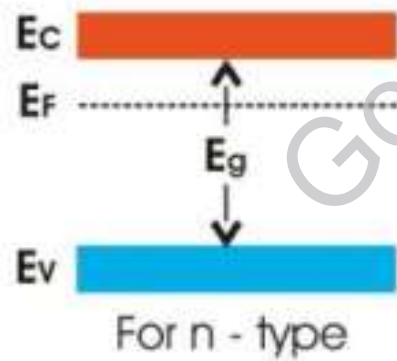
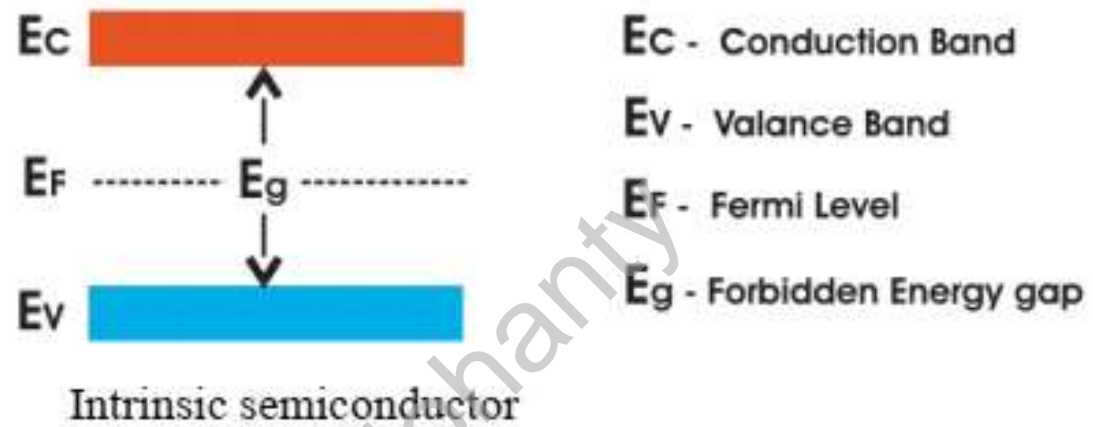
$$e^{(2E_F - E_c - E_v)/kT} = \left( \frac{m_h}{m_e} \right)^{3/2}$$

$$\frac{2E_F - E_c - E_v}{kT} = \frac{3}{2} \ln \frac{m_h}{m_e} \quad \longrightarrow \quad E = \frac{E_c + E_v}{2} + \frac{3}{4} kT \ln \frac{m_h}{m_e}$$

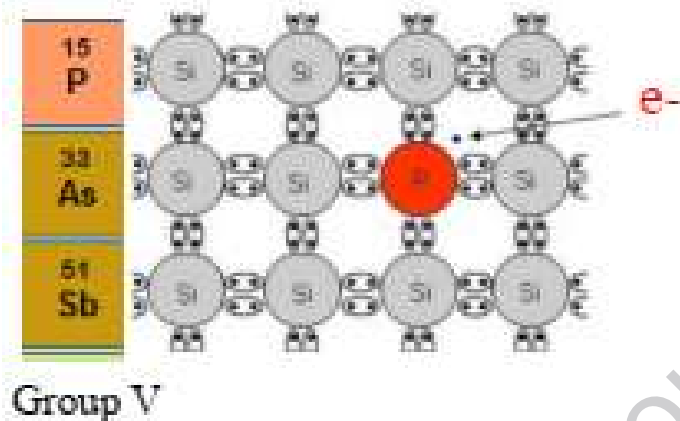
If  $m_e$  and  $m_h$  are same then  $E_F = \frac{E_c + E_v}{2}$

Fermi level is at the center of the band gap  $E_g$  for an intrinsic semiconductor

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

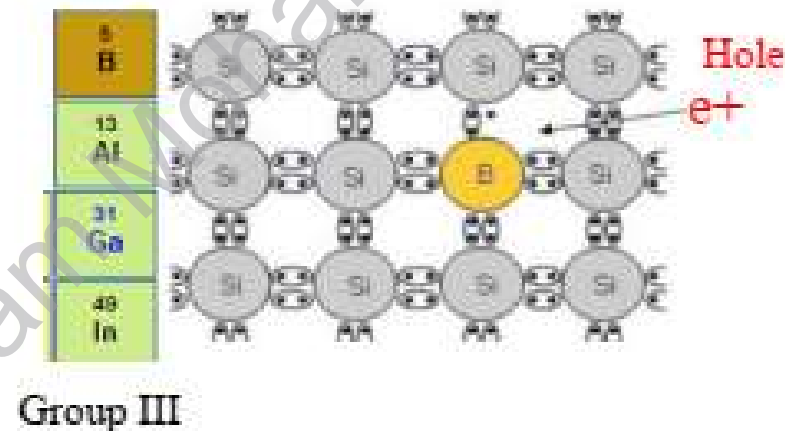


# Extrinsic semiconductors



## N-Type semiconductor

- By doping Si or Ge with **Group V** elements
- Majority carriers: **electrons**



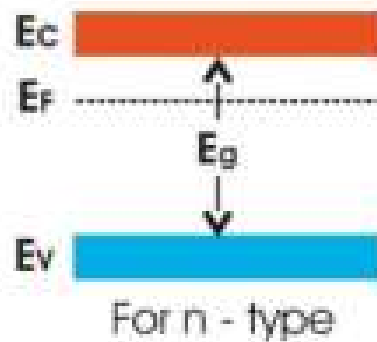
## P-Type semiconductor

- ✓ By doping Si or Ge with **Group III** elements
- ✓ Majority carriers: **holes**



# Extrinsic semiconductors

## N-Type semiconductor

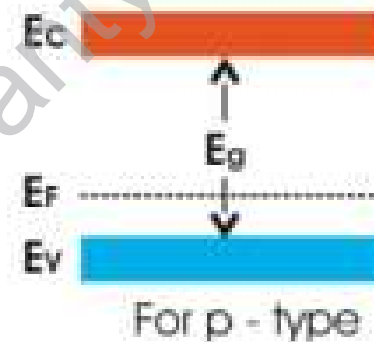


$$E_F = E_c - kT \ln \frac{N_c}{N_d}$$

k-Boltzmann's constant, T-temperature,  $N_a$  and  $N_d$  density of acceptor and donor atoms,  $N_v$  and  $N_c$  density of holes in the valence band and density of electrons in the conduction band

**Fermi level lies just below the conduction band**

## P-Type semiconductor



$$E_F = E_v + kT \ln \frac{N_v}{N_a}$$

**Fermi level lies just above the valence band**

*Confused electron*



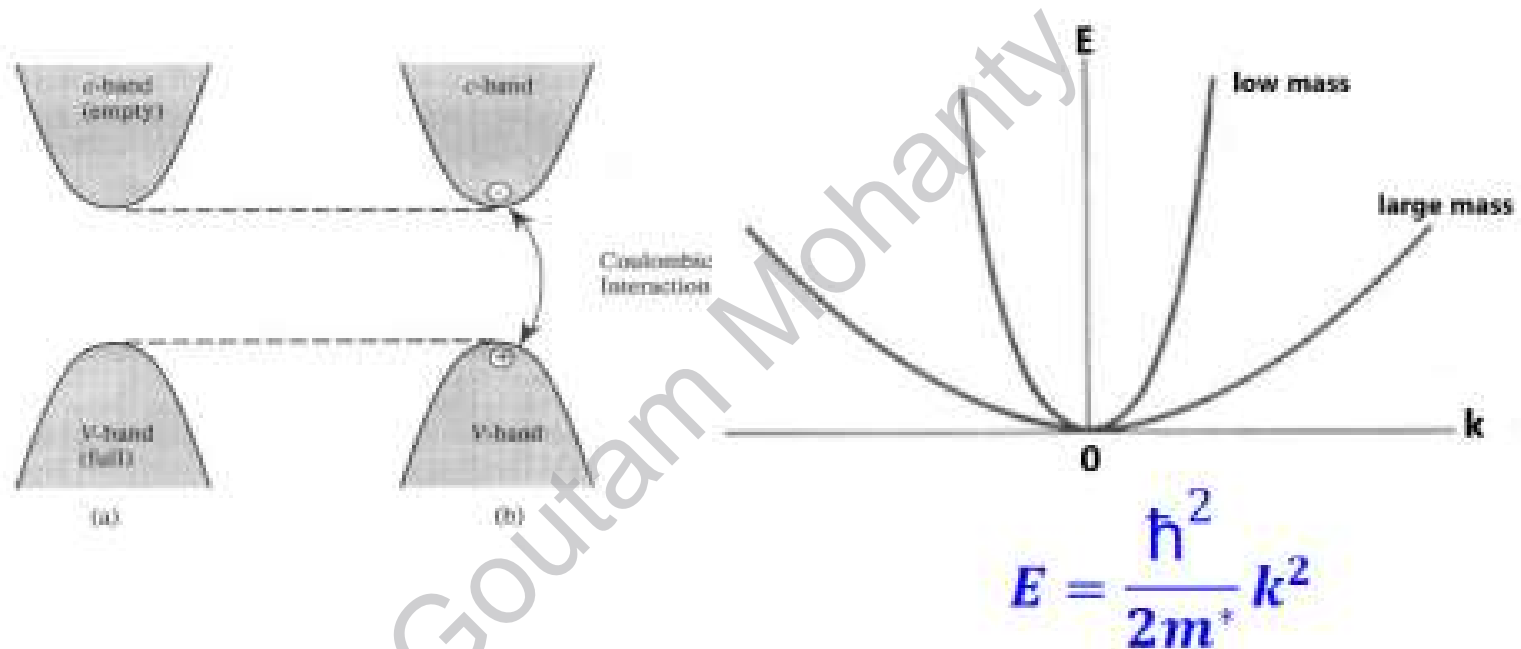
*Confused hole*



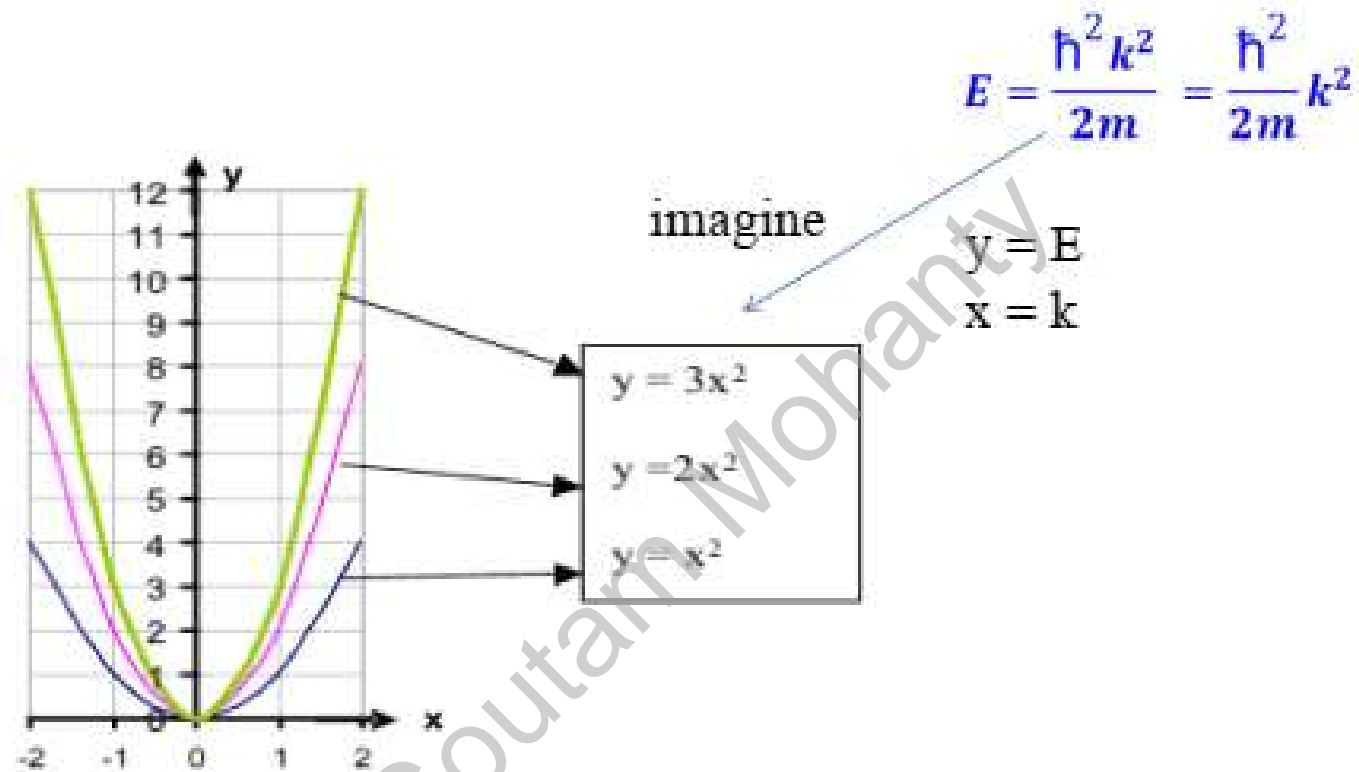
Let's focus on  
Effective Mass

Goutam Mohanty

## Effective Mass ( $m^*$ ) electrons and Holes



The concept of effective mass ( $m^*$ ) introduced to explain the curvature of the E-k diagram -



If the same electron in energy bands shows different shape then the mass must be different??

Effective mass concept formulated to explain it..

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

For free electron theory  $m=m^*$

Differentiating the above equation we get

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

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

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

Effective mass is inversely proportional to the curvature of the band

There are crystals in which the effective mass of the carriers is much larger or much smaller than  $m_0$ .

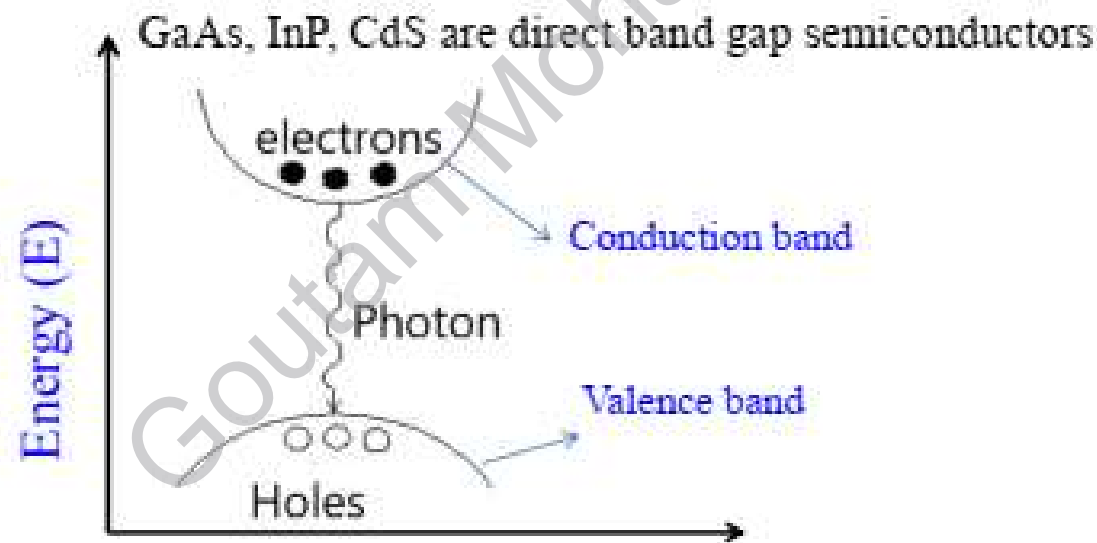
The effective mass may be anisotropic, and it may even be negative.

The important point is that the electron in a periodic potential is accelerated relative to the lattice in an applied electric or magnetic field as if its mass is equal to an effective mass.



## Direct Band gap semiconductors

In E-k diagram, when the lowest-energy point of the conduction band lies directly above the highest-energy point of the valence band in a semiconductor, the movement of a electron across the band gap conserves momentum and the gap is classified as "direct"



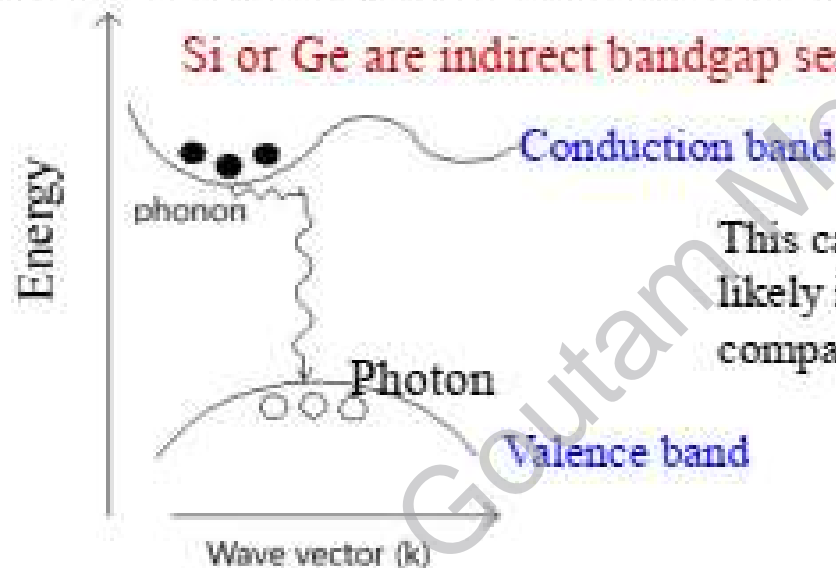
optical transitions more likely in materials with direct band gap compared to indirect bandgap.

k-Vector

Used in solar cell, LED etc

## Indirect Band gap semiconductors

When the highest-energy point of the valence band is not directly below the lowest-energy point in the conduction band, a phonon must carry away the momentum offset if a transition is to occur between the valence and conduction band.



This causes optical transitions to be much less likely in materials with indirect band gap compared to direct bandgap semiconductors.

Indirect band gap: Transition assisted with phonon ( quantized lattice vibrations)

## Direct band gap

- Bottom of conduction band(CB) lies directly above top of the valence band(VB)
- Electron recombines with holes gives photon
- The photon have energy equal to the band gap
- It is radiative recombination
- It is used to build light emitting devices
- Eg) GaAs

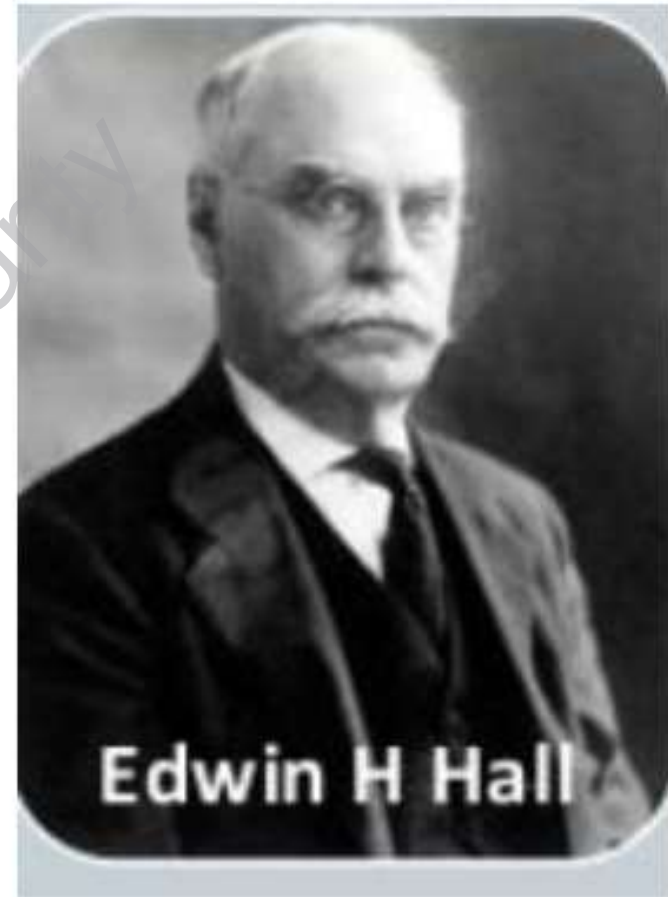
## Indirect band gap

- Bottom of CB not lies directly above the top of VB
- So for the conservation of momentum electron losses its energy by interacting with phonons
- The electron and hole recombines getting energy as form of heat
- It is Non radiative recombination
- Eg) Si, Ge

**Today we are going to learn about**

## **HALL EFFECT AND ITS APPLICATIONS**

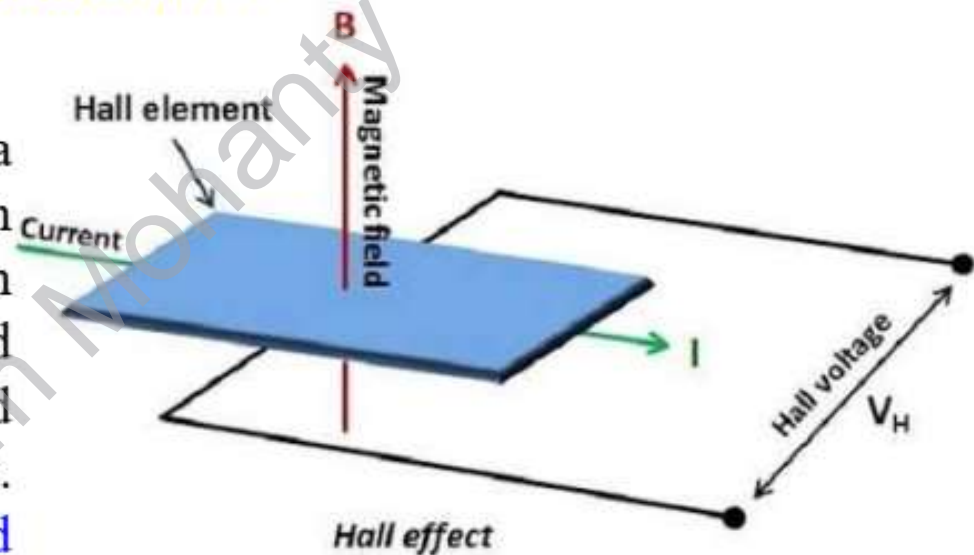
- ☐ Hall coefficient
- ☐ Hall voltage
- ☐ Applications of Hall effect



# Hall effect

It was discovered by **Edwin Herbert Hall** in 1879.

- ❑ The **Hall effect** is the production of a voltage (the **Hall voltage**) across an electrical conductor, transverse to an electric current in the conductor and to an applied magnetic field perpendicular to the current. Combined effect of Electric field and magnetic field on the flow of charges



- ❑ Observed much before the discovery of electron!. However, Could not be explained by the Classical free electron theory (1900) and Quantum free electron theory (1928). Positive and negative value of Hall coefficient



# HALL COEFFICIENT AND HALL VOLTAGE

## Derivation--

Force on the charge carriers due to the produced Hall electric field ( $\mathbf{E}_H$ ) is given by

$$\mathbf{F}_E = q\mathbf{E}_H \longrightarrow \text{Eq.1}$$

Force on the charge carriers due to the applied magnetic field ( $\mathbf{B}$ ) is given by

$$\mathbf{F}_M = q(\vec{v}_d \times \vec{B}) \longrightarrow \text{Eq.2}$$

Where  $v_d$  is the drift velocity and  $q$  is the electric charge of the carrier.

At equilibrium/stationary state these two forces must be equal, so from **Eq.1** and **Eq.2** we get

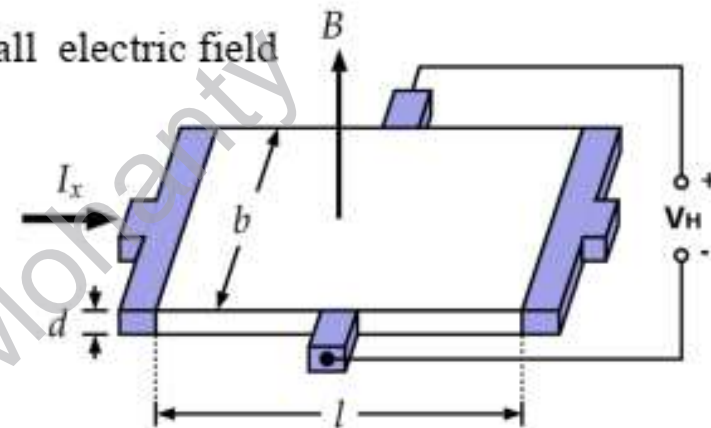
$$\mathbf{F}_E = \mathbf{F}_M = q\mathbf{E}_H = q(\vec{v}_d \times \vec{B}) \longrightarrow \vec{E}_H = \vec{v}_d \times \vec{B} \longrightarrow \text{Eq.3}$$

If we talk about the magnitude **Eq.3** can be written as

$$E_H = v_d B \sin\theta$$

In the present case  $\theta$  is  $90^\circ$ , so we get

$$\vec{E}_H = \vec{v}_d \times \vec{B} \longrightarrow \text{Eq.4}$$



# HALL COEFFICIENT AND HALL VOLTAGE

## Derivation--

Consider  $n$  is the number of charge carriers per unit volume, then the current density can be written in terms of the drift velocity ( $v_d$ ) as follows

$$J = nqv_d \longrightarrow \text{Eq.5}$$

Substitute Eq.5 in Eq.4

$$E_H = v_d B \longrightarrow E_H = \frac{JB}{nq} \longrightarrow \text{Eq.6a}$$

If  $b$  is the width of the block, then hall electric field  $E_H$  can be related potential as

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

$V_H$  is known as the hall voltage and written as

$$V_H = E_H b = \frac{J B b}{nq} \longrightarrow \text{Eq.6}$$

# HALL COEFFICIENT AND HALL VOLTAGE

## Derivation--

Coefficient of proportionality  $1/nq$  is called the Hall coefficient and is denoted by  $R_H$ . So we have

$$R_H = \frac{1}{nq} \longrightarrow \text{Eq.7}$$

$R_H$  will be negative if the charge carriers are electrons and will be positive if the charge carriers are holes. So can be used to distinguish the type of semiconductors

To relate the Hall electric field ( $E_H$ ) to the applied electric field ( $E_x$ ) we use the relation for J,

$$J = \sigma E_x = \frac{E_x}{\rho} \quad \text{in} \quad E_H = \frac{JB}{nq}$$

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

Where  $\sigma$  and  $\rho$  are the electrical conductivity and resistivity, respectively of the slab under consideration

$$\frac{E_H}{E_x} = \frac{B}{\rho nq} \longrightarrow \text{Eq.8}$$

So can be used as an electric and magnetic field sensors. Also can be used to measure the resistivity and conductivity of the semiconductors/materials

# APPLICATIONS OF HALL EFFECT

1. To determine the resistivity and conductivity of semiconductors
2. To determine the Type of Semiconductors
3. To calculate the Carrier Concentration
4. To determine the Mobility (Hall Mobility)
5. To measure Magnetic Flux Density

## Commercially available devices

1. Position and motion sensors
2. IC switch
3. GPS
4. Fuel injector
5. Sensors to detect rotation speed

In the presence of large magnetic field strength and low temperature, one can observe the quantum Hall effect, which is the quantization of the Hall resistance. This is now the official standard for electrical resistance.

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Goutam Mohanty