

## **Physics of Semiconductors**

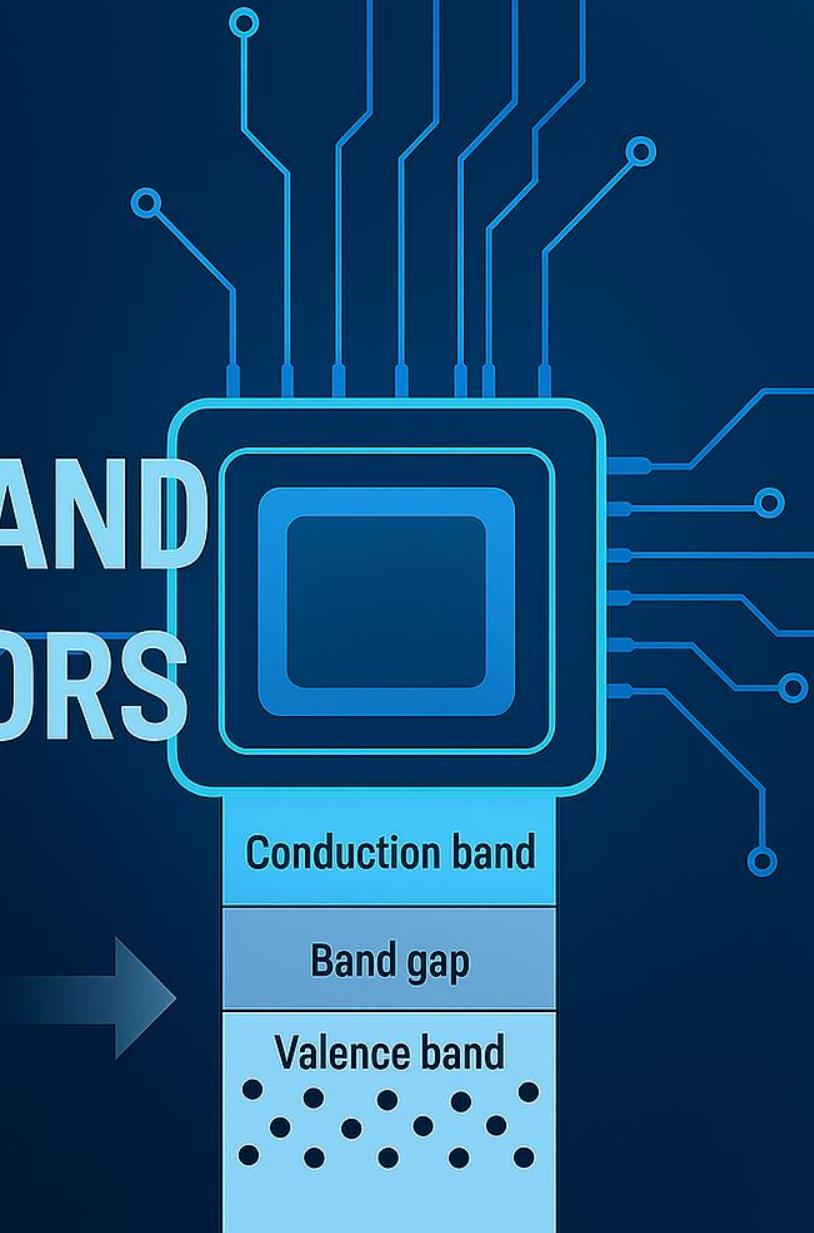
**(SUBJECT CODE: 03019201BS01)**

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# UNIT 1: BAND THEORY AND SEMICONDUCTORS



# **What to Study in Modern Physics !!!**

- Band structure of solid materials
- E-k diagram
- Direct and Indirect band gap
- Effective mass
- Concept of Fermi Energy
- Density of states
- Fermi Level in Intrinsic and Extrinsic Semiconductors
- Ohmic and Schottky Junction

# Material Classification by Electrical Resistivity

Materials in physics are often classified based on how well they conduct electricity. This is where **electrical resistivity** becomes a key parameter.

## What is Resistivity?

- **Resistivity** is a fundamental property of a material that quantifies how strongly it resists the flow of electric current.
- It's a measure of how much a material opposes the movement of charge carriers (like electrons) through it.
- A higher resistivity indicates a greater resistance to current flow, while a lower resistivity suggests a material that conducts electricity more easily.

$$\rho = (R * A) / L$$

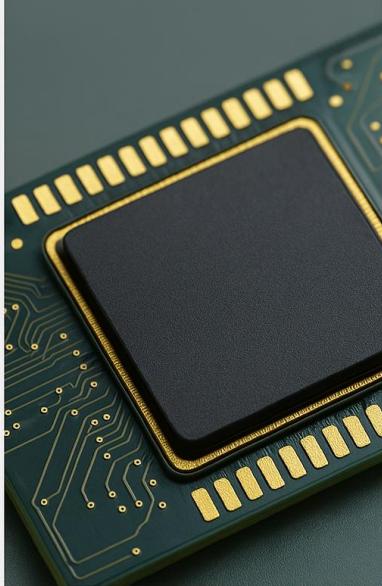
- The Standard Unit (S.I.) for resistivity is **ohm-meter ( $\Omega \cdot m$ )**.
- Resistivity is an intrinsic property of a material and depends on factors like:
  - Temperature
  - Material type
  - Number of charge carriers
  - Relaxation time

# Material Classification by Electrical Resistivity

**Conductors:** Allow easy flow of electric current.

**Semiconductors:** Have moderate resistivity, behavior varies with conditions.

**Insulators:** Strongly oppose current flow.



**CONDUCTOR**

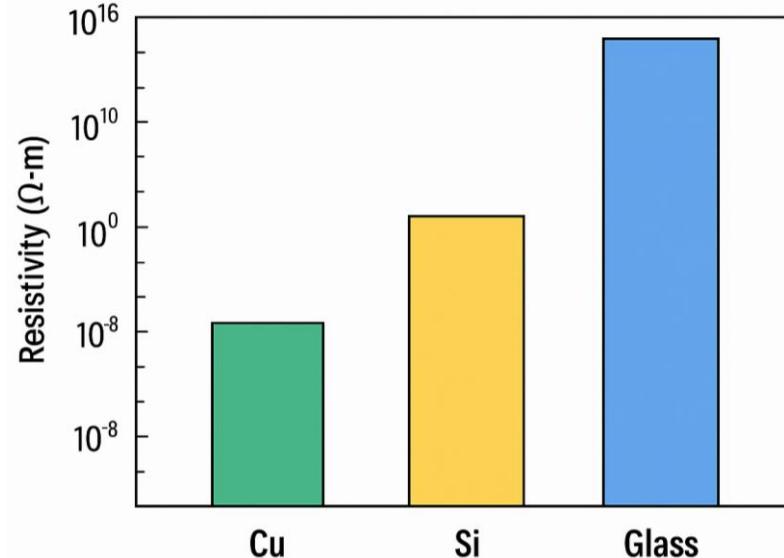
**SEMICONDUCTOR**

**INSULATOR**

# Classification Based on Resistivity

Materials are classified as follows based on the magnitude of their resistivity:

- Conductors: Resistivity  $\approx 10^{-8} \Omega\cdot m$ 
  - Example: Copper (Cu), Silver (Ag)
- Semiconductors: Resistivity  $\approx 10^3 \Omega\cdot m$ 
  - Example: Silicon (Si), Germanium (Ge)
- Insulators: Resistivity  $> 10^6 \Omega\cdot m$ 
  - Example: Glass, Rubber, Mica Visual

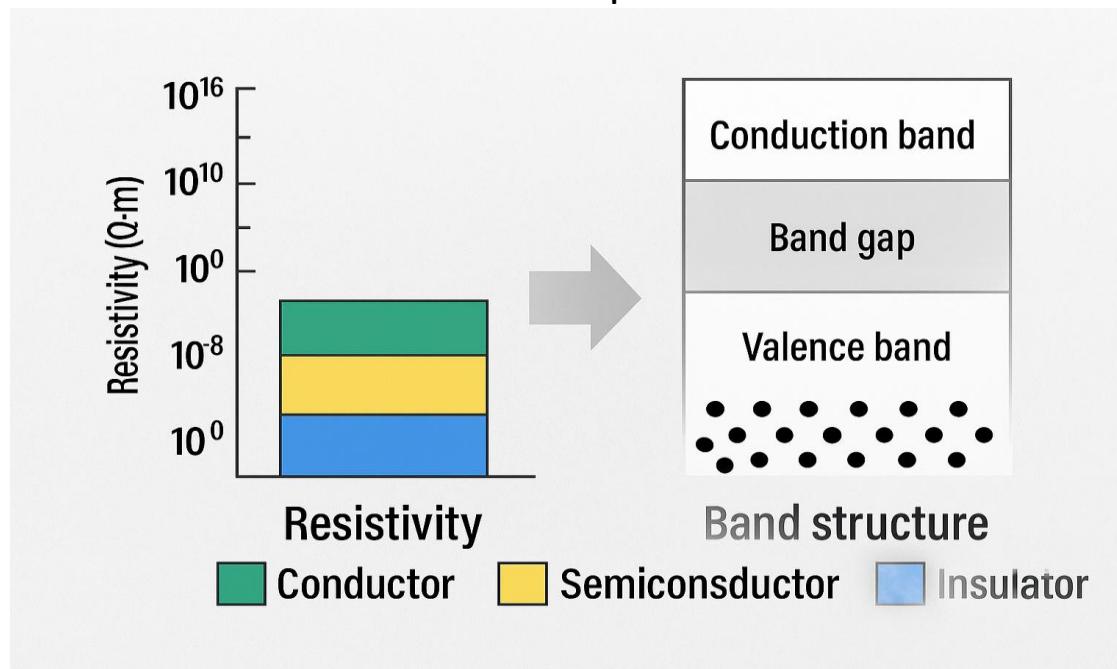


Material Type	Example Materials	Resistivity Range ( $\Omega\cdot m$ )
Conductor	Copper, Silver, Gold	$10^{-8}$ to $10^{-6}$
Semiconductor	Silicon (intrinsic), Germanium	$10^{-3}$ to $10^3$
Insulator	Glass, Rubber, Quartz	$10^8$ to $10^{16}$

# Limitations of Resistivity-Based Classification

While resistivity is useful for macroscopic classification, it doesn't explain:

- Temperature-dependent conductivity.
- Carrier generation (electrons and holes).
- Quantum behavior within solids this necessitates a deeper model: **Band Theory**, which explains electronic behavior at the microscopic level.



# Recap & Interactive Quiz

## Quick Recap

- Resistivity helps classify materials as conductors, semiconductors, or insulators.
- It's defined by how much a material resists current.
- Real-world examples provide tangible insights.

## Quiz

1. Which of these has the highest resistivity:  
A) Copper    B) Glass    C) Silicon    D) All of the materials
2. Which property defines whether a material is a conductor or an insulator?

# Classical Free Electron Theory

- Band theory explains the behavior of electrons in solids.
- Over the years several theories were pitched based on classical and quantum mechanics.

## 1. Classical Free Electron Theory:

- This theory was first proposed by Paul Drude in 1900 and later extended by Lorentz in 1909. It is therefore also called as **Drude-Lorentz theory**.
- According to this theory, metals consist of positive ion cores and valence electrons. The ions cores are immobile and consist of positive nucleus and the bound electrons. The valence electrons get detached from the parent atoms during the process of formation of the metal and move randomly among these cores. Hence, they are known as free electrons.
- These free electrons are responsible for the electrical conductivity in metals and the velocities of free electrons obey the **laws of classical mechanics** i.e. Maxwell-Boltzmann distribution of velocities and energies.
- **According to Maxwell-Boltzmann distribution many electrons can simultaneously possess the same energy (or velocity).**

# Classical Free Electron Theory

- In this theory, it was assumed that the free electrons move in a region of constant potential.
- This theory successfully explained the Ohm's law and the high electrical conductivity of metals.
- **It failed to explain dependence of conductivity ( $\sigma$ ) on number of electrons (n).**
- **It could also not explain the variation of conductivity and resistivity due to external factors like temperature, light and impurities in case of semiconductor and insulators.**
- **These failures led to the birth of Quantum Free Electron Theory of Solids.**

# Quantum Free Electron Theory

- This theory was developed by Sommerfeld in 1928.
- This theory was based on particle nature of electrons and not on the wave nature of electrons.
- According to quantum theory, electrons obey Pauli Exclusion Principle i.e.
  1. no more than two electrons can occupy the same orbital and,
  2. two electrons in the same orbital must have opposite spins.
- Hence follow **Fermi-Dirac distribution**.
- According to quantum theory, only two electrons can occupy the same energy level.
- Hence even at 0K, conduction (or free) electrons occupy different discrete energy levels.
- Thus, this theory failed to explain distinction between conductors, insulators and semiconductors.

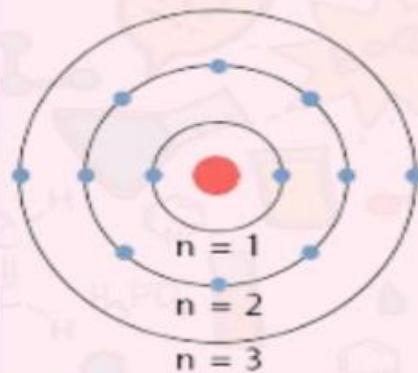
# Pauli's Exclusion Principle

## Statement

- No two electrons in an atom can have the same set of all four quantum numbers ( $n$ ,  $l$ ,  $m_l$ ,  $m_s$ ).

## Quantum Numbers

### Principle



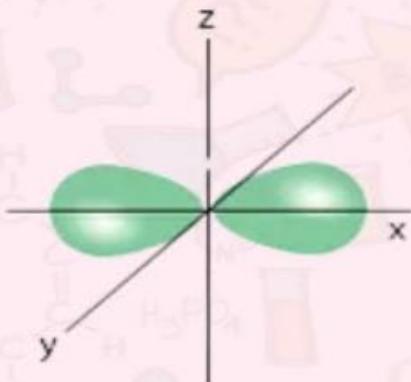
Distance of the electrons from nucleus

### Azimuthal



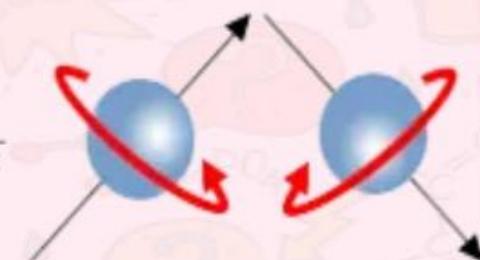
shape of the Orbital

### Magnetic



Orientation of the Orbital

### Spin

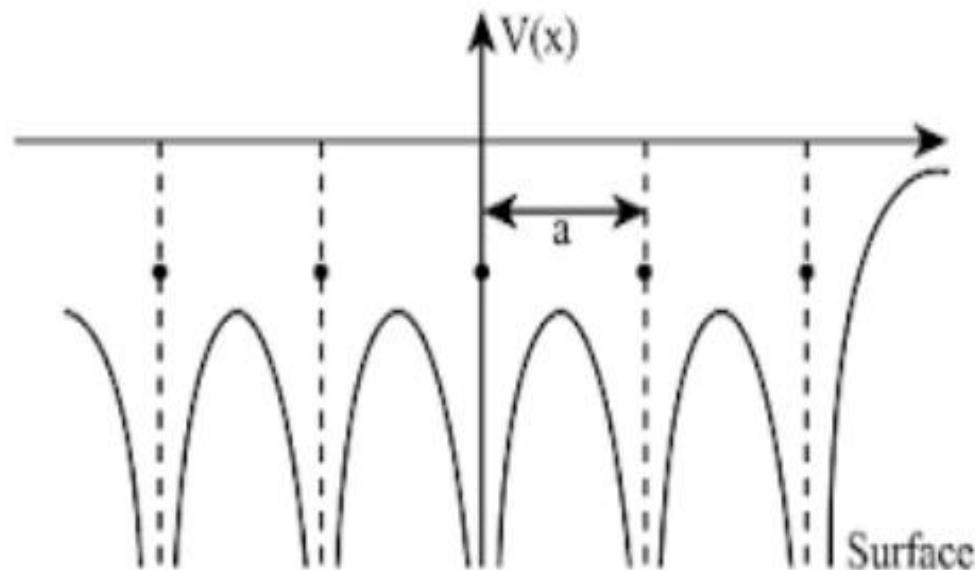
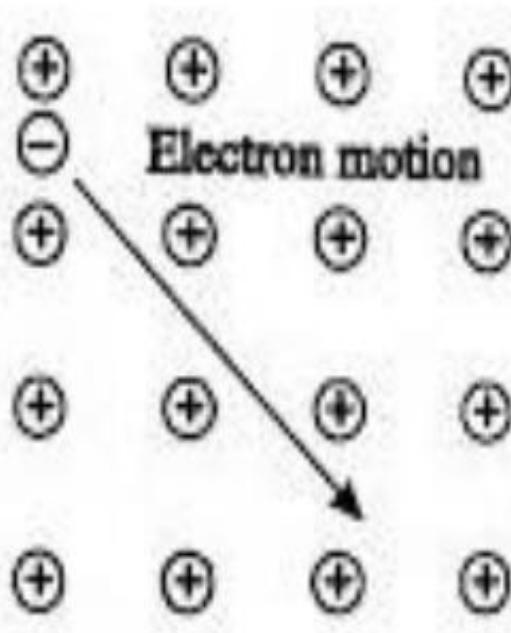


Orientation of the electron spin

\*Image Credit: Online Ace Academy

# Band Theory of Solids

- After the failure of Quantum free electron theory, Felix Bloch, in 1928, formulated the Band Theory of Solids.
- This theory is based on wave nature of electrons.
- **Electrons exhibit wave character as they move between atoms in a solid.**
- **It is also assumed that potential varies in a periodic manner in the solid.**  
Electrons move in a periodic potential provided by lattice.



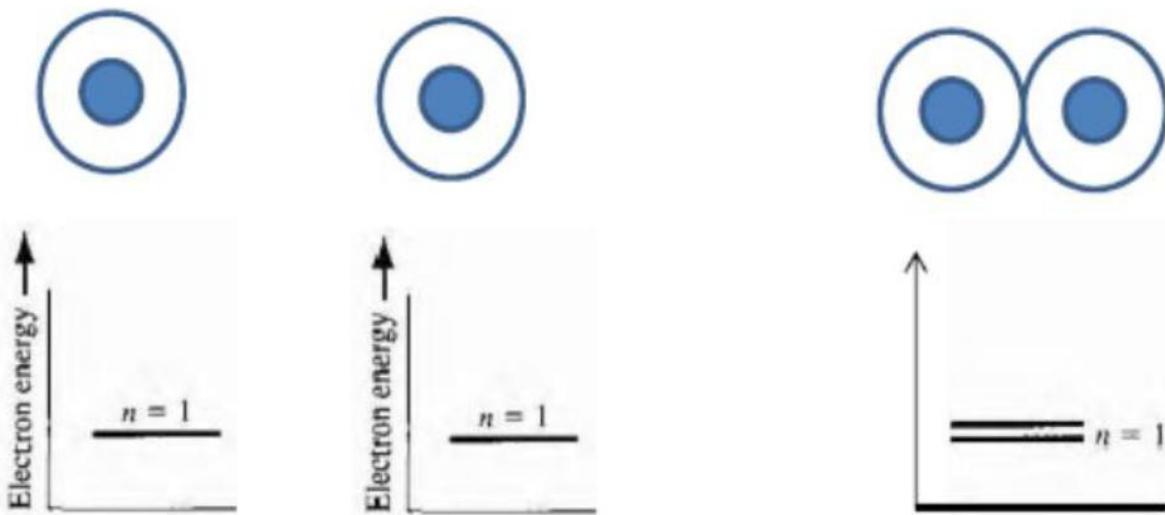
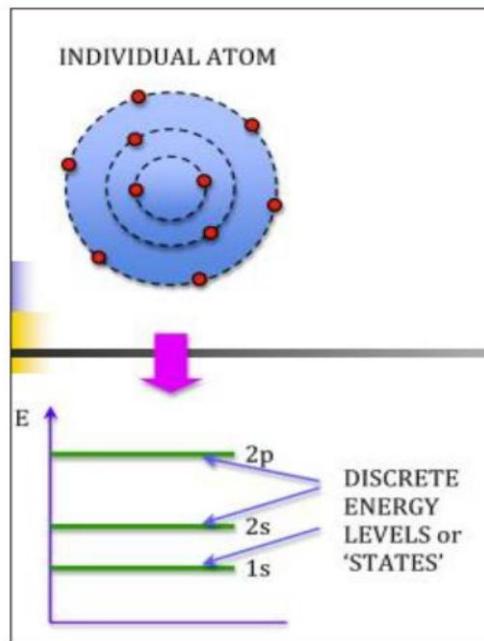
# Formation of Bands

## Isolated Atom:

- Each atom has discrete energy levels (e.g., 1s, 2s, 2p, etc.). These levels are well-separated and governed by Pauli's principle.

## Bringing Atoms Together:

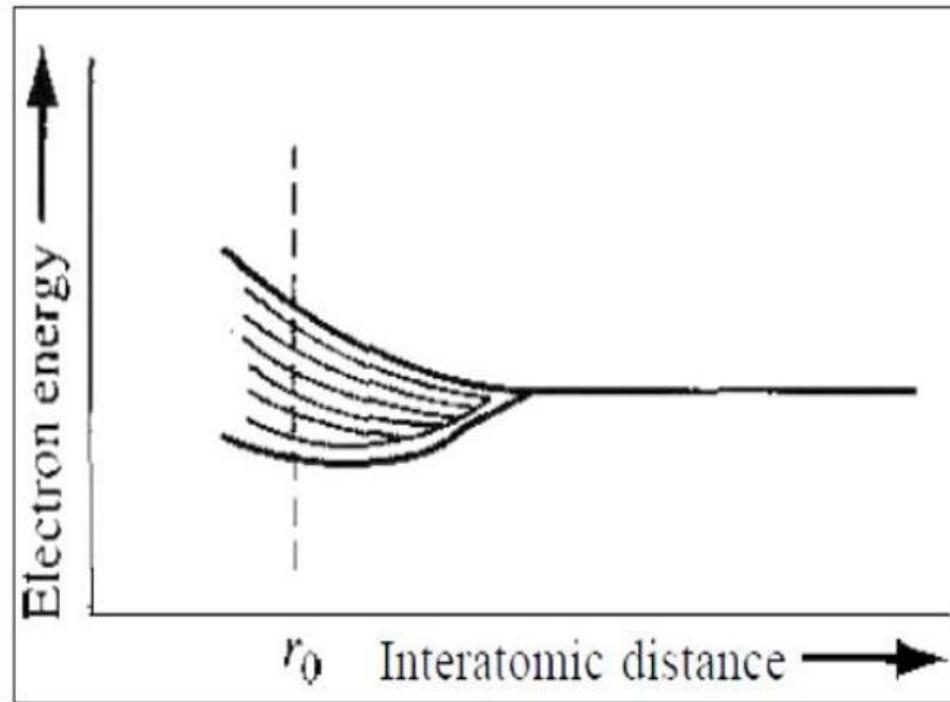
- In a solid, millions of atoms are arranged periodically.
- Their outer (valence) orbitals overlap due to proximity.



# Formation of Bands

## Energy Level Splitting:

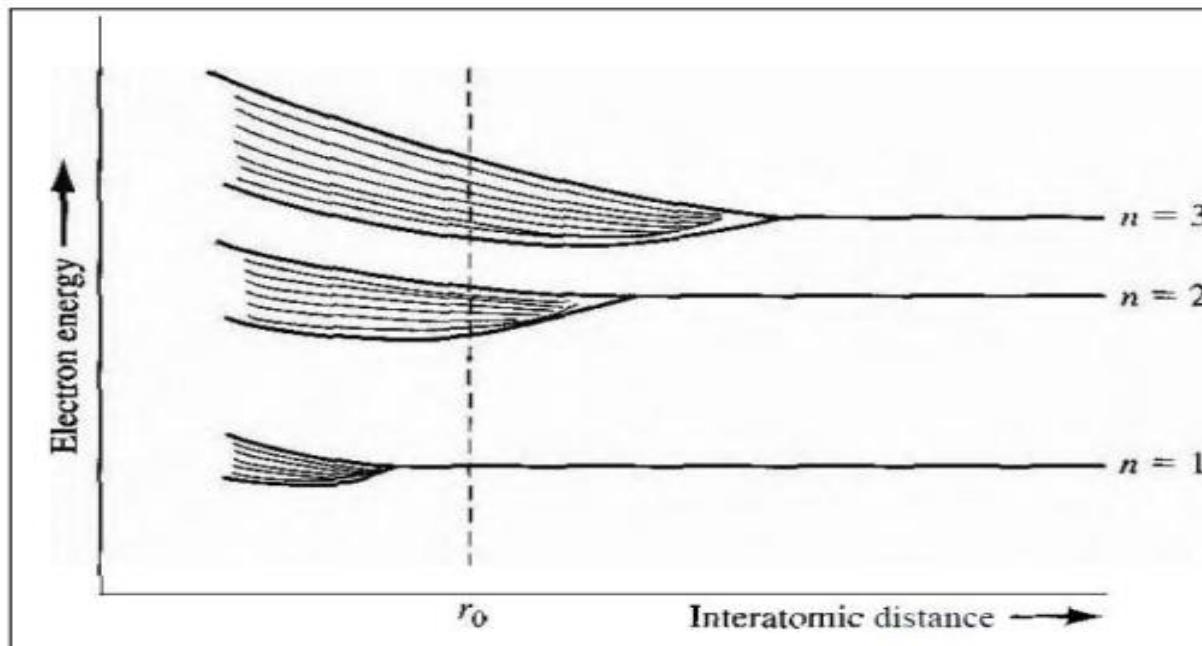
- Due to Pauli's principle, no two electrons in the entire crystal can occupy the same quantum state.
- So, when  $N$  atoms come together, each atomic energy level of  $n = 1$  splits into  $N$  closely spaced levels to accommodate all electrons uniquely.



# Formation of Bands

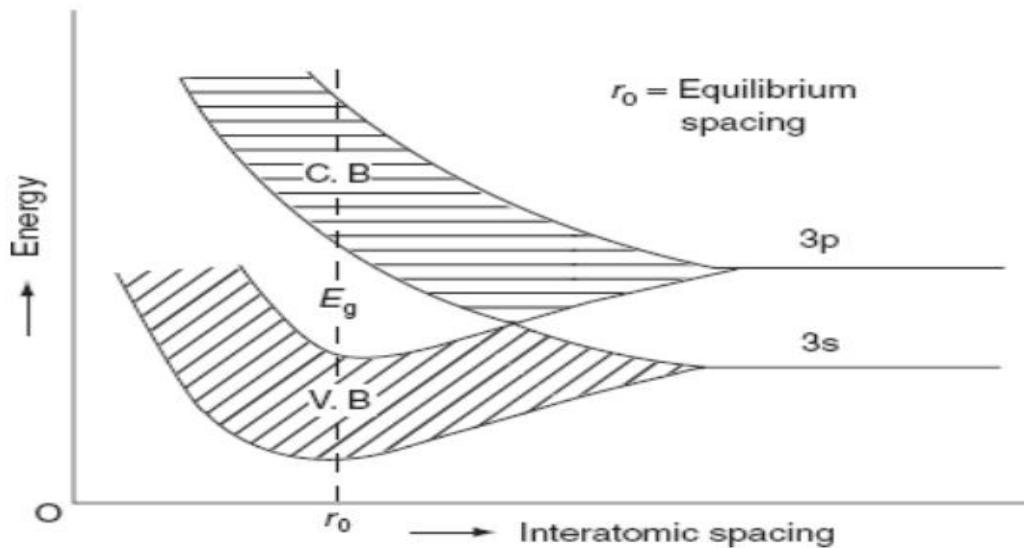
## Formation of Bands:

- Consider a periodic arrangement of atoms. Each atom contains electrons upto  $n=3$  energy level.
- If these atoms are brought together, the outermost electrons in the  $n=3$  energy shell will begin to interact and split into a band of allowed energies.
- As the atoms move closer, the electrons in the  $n=2$  shell, and finally the innermost electrons in the  $n=1$  shell, will also form two bands of allowed energies.



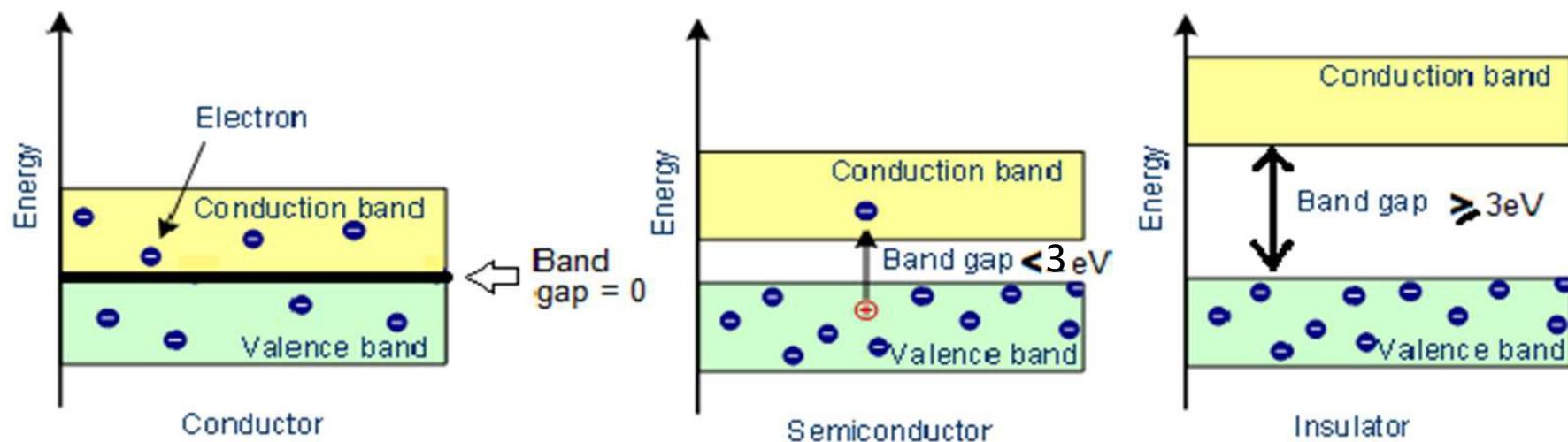
# Formation of Bands

- As the interatomic distance is further decreased, a split occurs between the upper and lower band.
- At equilibrium point the two bands are widely separated.
- The upper band (ideally empty) is called **Conduction Band** and the lower band (ideally completely filled) is called **Valence Band**.
- The energy gap/difference between the top of the valence band and bottom of the conduction band is called **Forbidden Energy Gap or Band Gap ( $E_g$ )**.
- For conductors the band gap is  $\sim 0\text{eV}$ , for semiconductors the band gap is in range of  $0.1 - 3\text{eV}$  and for insulators the band gap is  $> 3\text{eV}$ .



# Classification of Solids based on Band Theory

- **Conductors:** The solids in which conduction and valence band overlap each other are called conductors. Therefore, the energy gap between valence band and conduction band is zero.
- **Semiconductors:** The solids in which the conduction and valence bands are separated by a small energy gap of less than 3eV are called semiconductors.
- **Insulators:** The solids in which the conduction band and valence bands are separated by a large energy gap of  $\geq 3\text{eV}$  are called insulators.

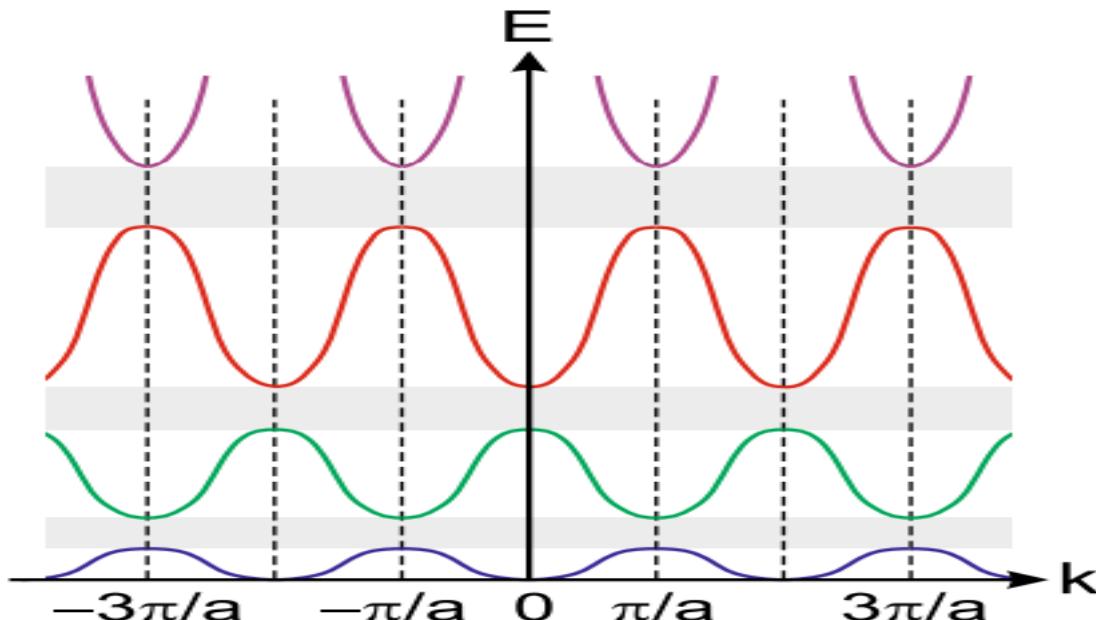


# E-K Diagram

- In eq. (9) which is given below:

$$P \frac{\sin \alpha a}{\alpha a} + \cos \alpha a = \cos K a; \quad \text{where, } K = \frac{2\pi}{\lambda}$$

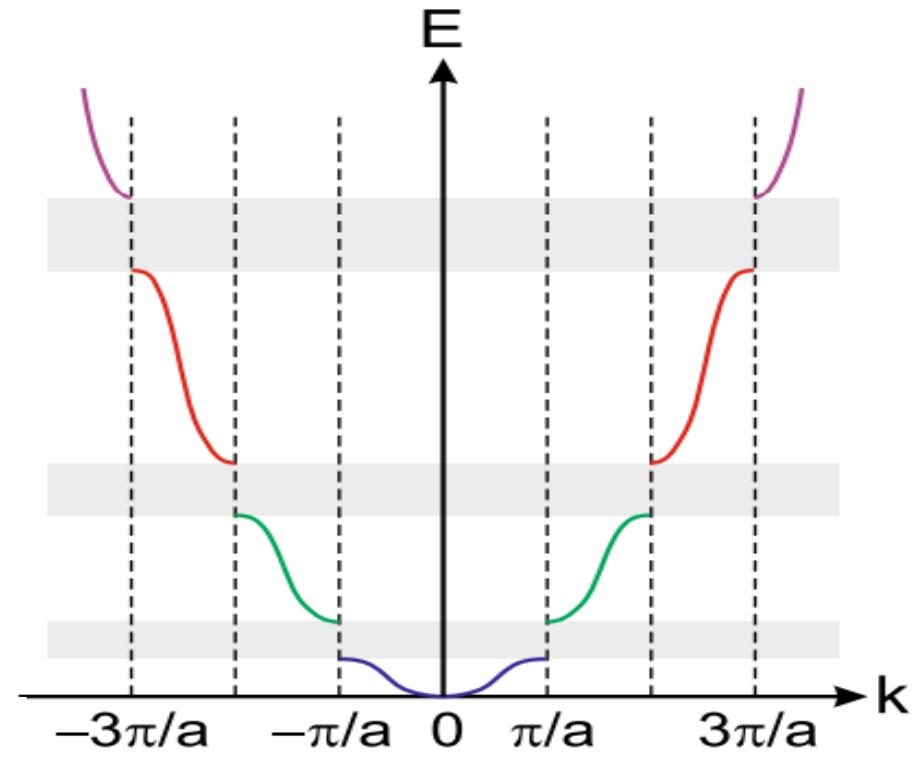
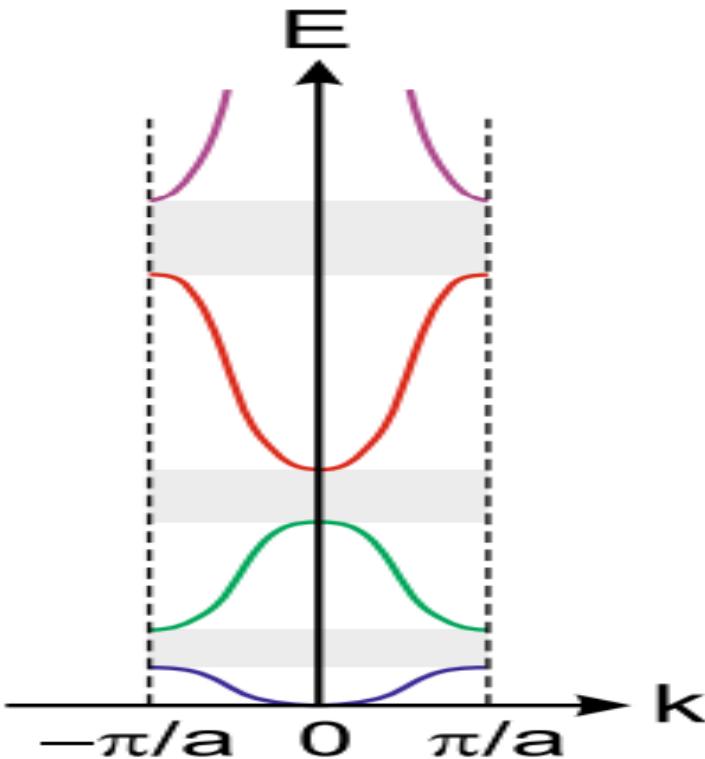
- The R.H.S. of the eq. is an even periodic function and its value does not change whether  $Ka$  is positive or negative.
- As a result, the total energy  $E$  of the electron is an even periodic function of  $K$  with a period of  $\frac{2\pi}{a}$ . This periodic repetition of energy is shown in figure below.



This representation is known as periodic zone scheme.

## E-K Diagram

- The above shown diagram can be considered as obtained by the repetition of the region  $-\frac{\pi}{a} < K < \frac{\pi}{a}$ .
- This is the first Brillouin zone.
- It can also be represented in the form of reduced zone scheme and extended zone scheme respectively as shown below.



# E-K Diagram

- Discontinuities occur at  $K = \pm \frac{n\pi}{a}$ , where  $n = 1, 2, 3, \dots$
- These  $K$  values define the boundaries of the first, second and third Brillouin zones.
- If we consider a line representing  $K$  values, divided into energy discontinuities into segments of length  $\pm \frac{\pi}{a}$  as shown in figure above, these line segments are called Brillouin zones.

## IMPORTANCE OF E-K DIAGRAM:

The E-K diagram gives us the following information.

- It is useful to study the band structure in materials.
- It gives the energy momentum relationship for an electron in a crystal.
- It gives an idea of band gap in materials.

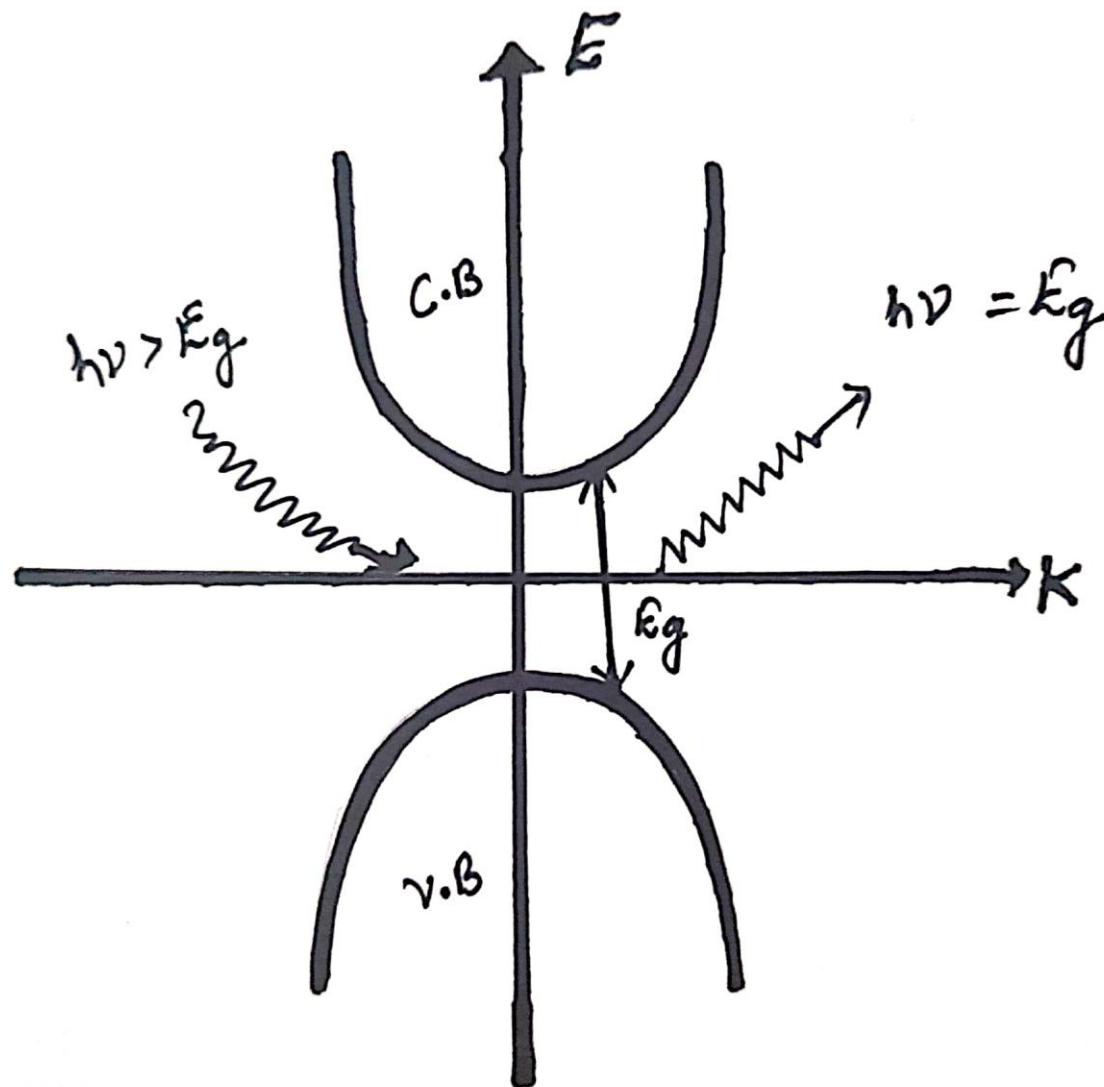
# Direct and Indirect Band gap materials

- In real 3D crystal structure of materials, the spacing between atoms may not be same in all directions.
- This gives rise to different band structure in materials.
- Therefore, along different directions the curvature of E-K diagram will be different.
- This gives rise to two types of semiconductors:
  1. Direct band gap semiconductors
  2. Indirect band gap semiconductors

# Direct Band gap materials

- In direct bandgap semiconductor, the bottom of the conduction band and top of the valence band lies at the same value of K.
- In this, electron can directly excite or de-excite by the absorption or emission of photon and there is **no phonon involvement** in the process of excitation and de-excitation.
- If a photon incident of energy  $h\nu$ ,  $h\nu > E_g$ , there is absorption then electron of valence band will absorb this energy and excite to the conduction band and when it de-excite to valence band, then it will emit some energy i.e.  $h\nu = E_g$ .
- There is no requirement of phonon or lattice in the conservation of energy and momentum.
- Direct bandgap semiconductors are used in light-emitting applications like LED and LASER. Ex. GaAs, CdS, ZnS, CdSe etc.

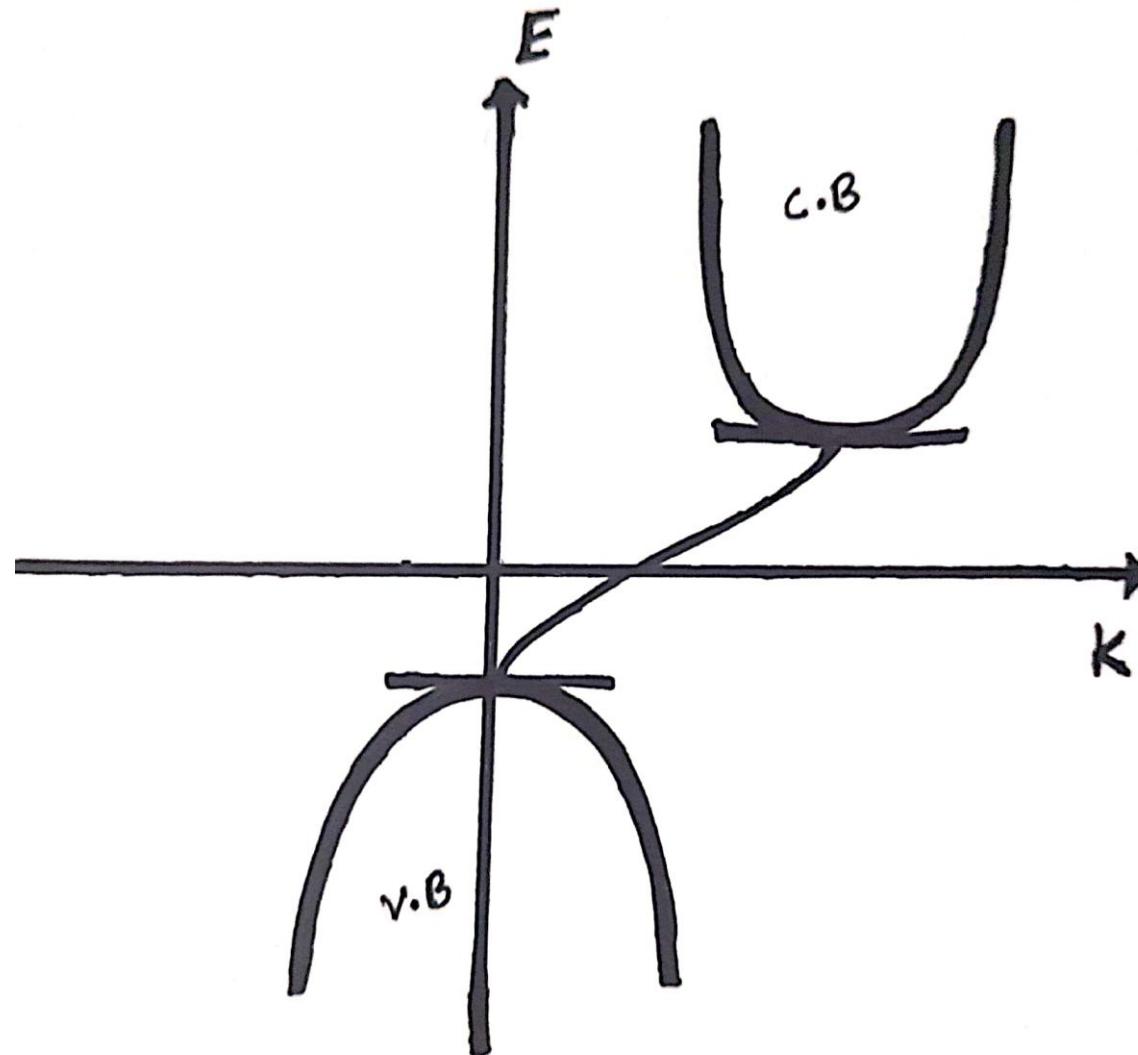
# Direct Band gap materials



# Indirect Band gap materials

- In indirect bandgap semiconductor, top of the valence band and bottom of the conduction band lies at different values of K.
- If an electron goes from the top of the valence band to the bottom of the conduction band, it has to change its energy as well as wave-vector K.
- For momentum and energy conservation, there is the involvement of phonon in the conservation process.
- If there is de-excitation of the electron, then not all the energy will be emitted in the form of the photon but some energy is emitted in the form of phonons i.e. some part is transferred to the lattice, and the lattice will vibrate and generate heat.
- So indirect bandgap semiconductor bandgap semiconductors are not suitable for light emission. Ex. Si, Ge, GaP, SiC, etc.

# Indirect Band gap materials



# Comparison between Direct and Indirect Band gap materials

Feature	Direct Band Gap	Indirect Band Gap
k-position alignment	Same	Different
Transition type	Photon only	Photon + phonon
Light emission	Strong (e.g., GaAs)	Weak (e.g., Si)
Applications	LEDs, lasers	Solar cells, transistors

# Effective Mass of Electron

- An electron in a crystal interacts with the lattice potential, hence its response to external force is different from a free electron.
- The energy of an electron under lattice potential is given by:

$$E = \frac{n^2 \pi^2 \hbar^2}{2ma^2}$$

- And the energy of a free electron is given by:

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

- Hence the deviation of electrons behavior is taken into account by considering electrons to have effective mass  $m^*$ .

# Effective Mass of Electron

- Let us consider an electron in external electric field  $E$ . when this field acts on electron for a small time  $dt$ , electron gains some energy

$$dE = eEdx = eEvdt \quad \text{---(1)}$$

- According to de-Broglie theory, the velocity of an electron with wave vector  $K$  is the same as group velocity of wave representing the electron i.e.

$$v = \frac{d\omega}{dK}$$

- Where  $\omega$  is the angular frequency and is related to the electron energy  $E$  by the relation  $E = \hbar\omega$ .

# Effective Mass of Electron

- In terms of energy, the velocity is expressed as

$$v = \frac{1}{\hbar} \left( \frac{dE}{dK} \right) \quad \text{---(2)}$$

- Putting eq. (2) in (1) we get,

$$dE = \frac{eE}{\hbar} \frac{dE}{dK} dt$$

$$\frac{dK}{dt} = \frac{eE}{\hbar} \quad \text{---(3)}$$

- Now differentiating eq. (2) w.r.t.  $t$  gives the acceleration,

$$a = \frac{dv}{dt} = \frac{eE}{\hbar^2} \left( \frac{d^2E}{dK^2} \right) \quad \text{---(4)}$$

- Comparing it with classical eq. of  $a$

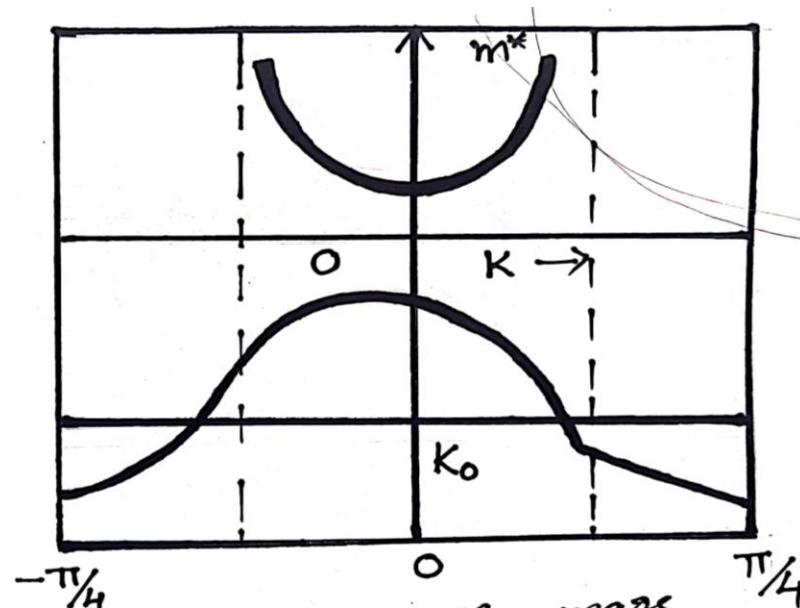
$$a = \frac{eE}{m} \quad \text{---(5)}$$

# Effective Mass of Electron

- This gives the effective mass  $m^*$

$$m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dK^2}\right)} \quad \text{---(2)}$$

- Here  $m^*$  is represented as a function of  $K$ .
- $m^*$  can be positive and can be negative.
- $m^*$  becomes infinite at point of inflection  
i.e. at  $K = K_0$ .



Plot of effective mass  
as a function of  $K$

# Effective Mass of Electron in C.B.

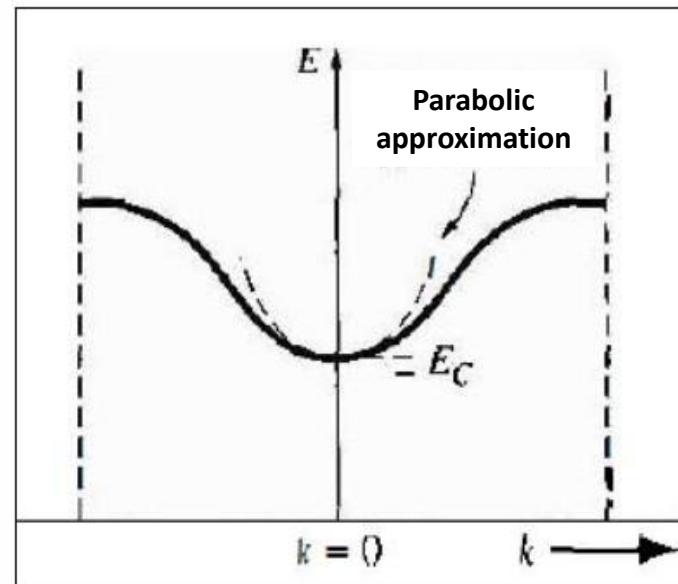
- The energy of electron near the bottom of the conduction band can be approximated by parabola.
- So, we can write,

$$E - E_C = c_1 K^2 \quad \text{---(3)}$$

- Here,  $E_C$  is the bottom of the conduction band.
- For  $K = 0, E = E_C$
- For  $K \neq 0, E > E_C$
- Therefore,  $c_1$  must be positive.
- Double differentiating eq. (3) and comparing it with eq. (2) we get,

$$m^* = \frac{\hbar^2}{2c_1} \quad \text{---(4)}$$

- Since,  $c_1$  is positive, mass of electron is also positive in conduction band.



# Effective Mass of Electron in V.B.

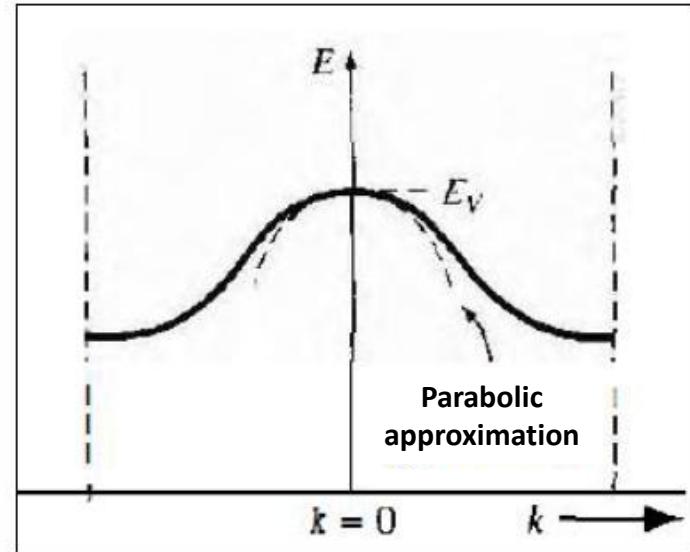
- The energy of electron near the top of the valence band can be approximated by parabola.
- So, we can write,

$$E_V - E = c_2 K^2 \quad \text{---(5)}$$

- Here,  $E_V$  is the top of the valence band.
- For  $K = 0$ ,  $E = E_V$
- For  $K \neq 0$ ,  $E < E_V$
- Therefore,  $c_1$  must be negative.
- Double differentiating eq. (5) and comparing it with eq. (2) we get,

$$m^* = -\frac{\hbar^2}{2c_2} \quad \text{---(6)}$$

- Since,  $c_2$  is negative, mass of electron is also negative in valence band.



# Electron vs Hole Effective Mass

- Electrons and holes have different effective masses.
- The effective mass of hole is often higher than electron and this impacts the mobility and recombination rates.
- Mobility is given by

$$\mu = \frac{q\tau}{m^*}$$

- where q = charge;  $\tau$  = scattering time
- Lower effective mass means higher mobility and vice versa.

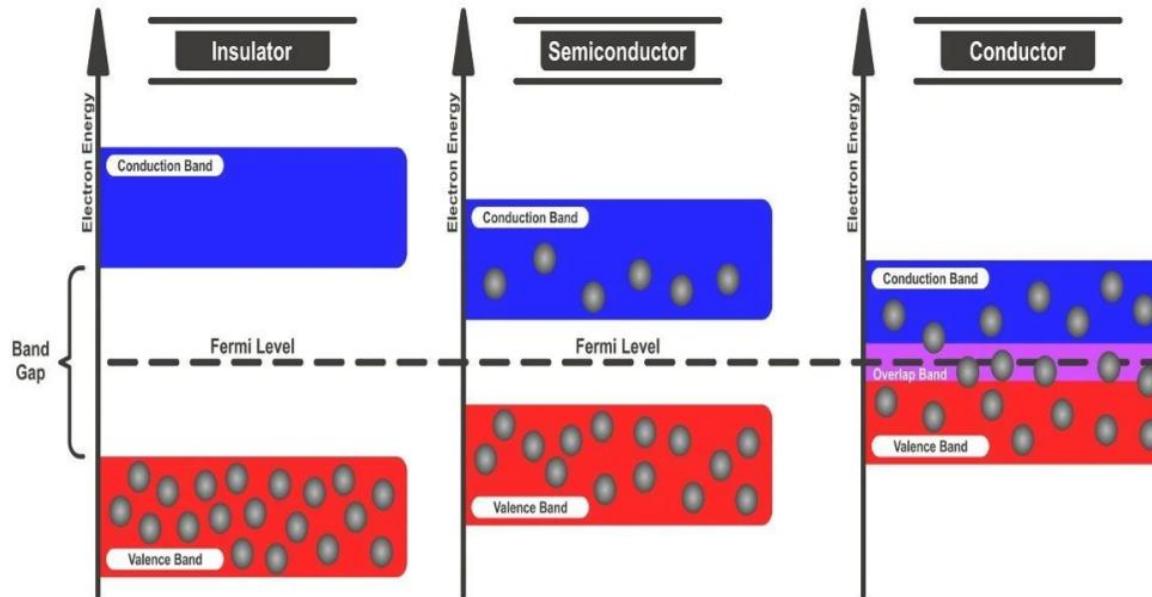
Material	Electron m*	Hole m*	Mobility (cm <sup>2</sup> /V*s)
Si	~0.26	~0.39	~1400
Ge	~0.12	~0.29	~3900
GaAs	~0.067	~0.5	~8500

- High mobility → faster transistors, better frequency response.
- Low mobility → slower switching, more heat

# Concept of Fermi Energy

## What Is Fermi Energy?

- Fermi Energy ( $E_F$ ) is the highest occupied energy level at absolute zero (0K) temperature.
- It defines the boundary between filled and unfilled states in a material.
- Crucial for predicting electron behavior in metals and semiconductors.
- The diagram below is an example of an energy band diagram. The upper box represents the conduction band; the lower box represents the valence band.



# Concept of Fermi Energy

- The electrons that occupies the energy levels are described by Fermi-Dirac distribution as the figure below, the distribution takes on the form of:

$$f(E) = \frac{1}{1 + \exp\left[\frac{E - E_F}{kT}\right]}$$

Where,

- $f(E)$  = factor or probability of occupation of a state with energy ( $E$ ).
- $E_F$  is the fermi level energy.
- $k$  is the Boltzmann constant and
- $T$  is the absolute temperature.

We have two situations now:

- At  $T = 0\text{K}$
- At  $T > 0\text{K}$

# Concept of Fermi Energy

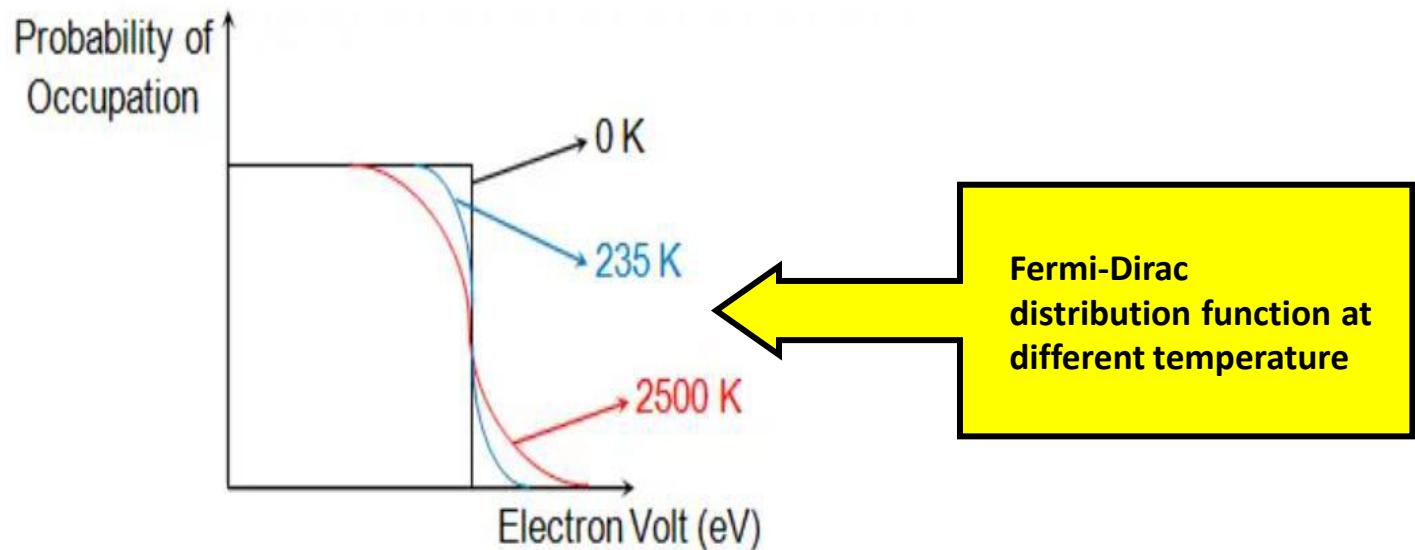
At T = 0K

- Electrons occupy energy levels in pairs starting from the bottom of the band up to an upper level designated as E.
- Fermi level E can be, therefore, defined as the uppermost filled energy level in a conductor at 0 K.
- Let us apply Fermi-Dirac equation to the solid taking T = 0K.
- For energy levels E lying below  $E_F$ ,  $E < E_F$ ,  $E - E_F$  is a negative quantity in the above equation.
- So,  $f(E) = 1$
- This indicates that all the energy levels lying below  $E_F$  are completely filled.
- For energy levels E lying above  $E_F$ ,  $E > E_F$ ,  $E - E_F$  is a positive quantity in the above equation.
- So,  $f(E) = 0$
- This implies that all the energy levels lying above  $E_F$  are vacant.
- For  $E = E_F$ , the quantity  $(E - E_F) = 0$  and  $f(E)$  becomes indeterminant.

# Concept of Fermi Energy

At  $T > 0K$

- If we consider an electron at Fermi level, then  $E = E_F$ .
- So,  $f(E) = \frac{1}{2}$ .
- This implies that the probability of occupancy of Fermi level at any temperature above 0K is 0.5 i.e. 50%.
- We can thus define:
- **Fermi level as the energy level where the electrons have a probable occupancy of 50% at any finite temperature or temperature above 0K.**



# Density of States

- The ability of a metal to conduct electricity depends on the energy levels which are available for the electrons. Hence, it is essential to find the energy states which are available for the occupation of the electrons (charge carriers).

## Definition:

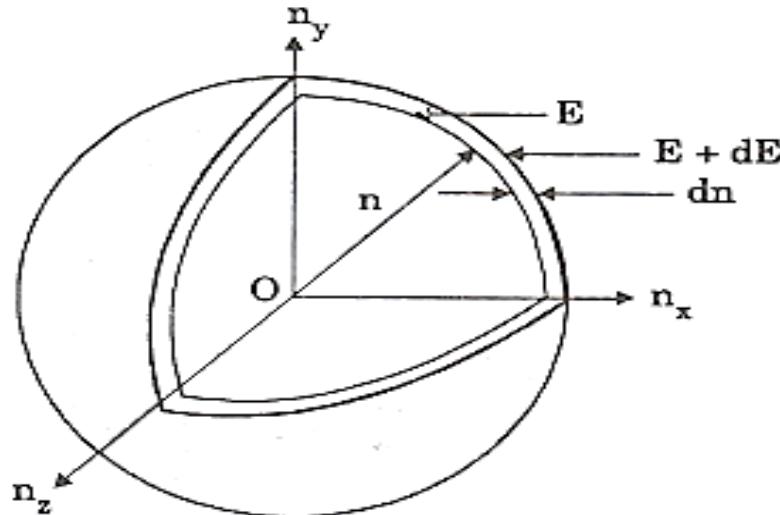
- It is defined as the number of available energy states per unit volume in an energy interval  $E$  and  $E + dE$ . It is denoted by  $Z(E)$ .
- It is given by:

$$Z(E) dE = \frac{\text{Number of energy states in between energy } E \text{ and } E + dE \text{ in a metal piece ( } N(E) dE \text{ )}}{\text{Volume of the metal piece ( V )}}$$

# Density of States

## Derivation:

- Let us consider a cubical material of side 'a'.
- In order to find the number of energy states available in the material in between the energy  $E$  and  $E + dE$ , a sphere is considered with three quantum numbers  $n_x$ ,  $n_y$ ,  $n_z$  as coordinate axes in three-dimensional space as shown in figure below.
- A radius vector  $n$  is drawn from origin 'O' to a point with co-ordinates  $n_x$ ,  $n_y$ ,  $n_z$  in this space. All the points on the surface of the sphere have the same energy  $E$ .



*Representation of energy states in quantum number space.*

# Density of States

- Thus,  $n$  such that  $n^2 = n_x^2 + n_y^2 + n_z^2$  denotes the radius of the sphere corresponding to energy  $E$ .

$$\therefore E = \frac{n^2 h^2}{8ma^2}$$

- Thus, the volume of the sphere of radius  $n$  is equal to the number of energy states upto  $E$ .
- Therefore, the number of energy states within a sphere of radius 'n'

$$= \frac{4}{3} \pi n^3 \text{ (Volume of the sphere)} \quad \dots(1)$$

- Since the quantum numbers  $n_x, n_y, n_z$  can have only positive integer values, only one octant of the sphere, i.e.,  $(1/8)^{\text{th}}$  of the spherical volume has to be considered.
- Only one octant of the sphere has all the quantum numbers  $n_x, n_y$  and  $n_z$  as positive.

# Density of States

- Therefore, the number of available energy states within one octant of the sphere of radius ' $n$ ' corresponding to energy  $E$

$$= \frac{1}{8} \left[ \frac{4}{3} \pi n^3 \right] \quad \dots(2)$$

- Similarly, the number of available energy states within one octant of the sphere of radius ' $n + dn$ ' corresponding to energy  $E + dE$

$$= \frac{1}{8} \left[ \frac{4}{3} \pi (n + dn)^3 \right] \quad \dots(3)$$

- The number of available energy states between the shells of radii  $n$  and  $n + dn$  i.e., between the energy values  $E$  and  $E + dE$  is determined by subtracting equation (2) from equation (3). Thus, we have

# Density of States

$$\begin{aligned}N(E) dE &= \frac{1}{8} \left[ \frac{4}{3} \pi (n + dn)^3 \right] - \frac{1}{8} \left[ \frac{4}{3} \pi n^3 \right] \\&= \frac{1}{8} \left( \frac{4\pi}{3} \right) \left[ (n + dn)^3 - n^3 \right] \\N(E) dE &= \left( \frac{\pi}{6} \right) \left[ n^3 + dn^3 + 3n^2 dn + 3n dn^2 - n^3 \right]\end{aligned}$$

$$[\because (a + b)^3 = a^3 + b^3 + 3a^2b + 3ab^2]$$

- Since  $dn$  is very small, the higher powers  $dn^2$  and  $dn^3$  are neglected.

$$N(E) dE = \frac{\pi}{6} 3n^2 dn$$

$$N(E) dE = \frac{\pi}{2} n^2 dn$$

$$N(E) dE = \frac{\pi}{2} n (n dn)$$

...(4)

- We know that the energy of an electron in a cubical metal piece of sides ' $a$ ' is given by (particle in a three-dimensional box problem).

# Density of States

$$E = \frac{\left(n_x^2 + n_y^2 + n_z^2\right) h^2}{8ma^2} \quad \left(\because n^2 = n_x^2 + n_y^2 + n_z^2\right)$$

$$E = \frac{n^2 h^2}{8ma^2} \quad \dots(5)$$

$$n^2 = \frac{8ma^2 E}{h^2} \quad \dots(6)$$

- Taking square root of the eqn (6), we have

$$n = \left[ \frac{8ma^2 E}{h^2} \right]^{1/2} \quad \dots(7)$$

- Differentiating the eqn (6), we get

$$2ndn = \frac{8ma^2 dE}{h^2}$$

$$\text{or } ndn = \frac{8ma^2 dE}{2h^2} \quad \dots(8)$$

# Density of States

$$2ndn = \frac{8ma^2 dE}{h^2}$$

$$\text{or } ndn = \frac{8ma^2 dE}{2h^2} \quad \dots(8)$$

- Substituting eqns (7) and (8) in eqn (4), we have

$$\begin{aligned} N(E) dE &= \frac{\pi}{2} \left( \frac{8ma^2 E}{h^2} \right)^{1/2} \left[ \frac{8ma^2 dE}{2h^2} \right] \\ &= \frac{1}{2} \cdot \frac{\pi}{2} \left( \frac{8ma^2 E}{h^2} \right)^{1/2} \left[ \frac{8ma^2 dE}{h^2} \right] \\ &= \frac{\pi}{4} \left( \frac{8ma^2}{h^2} \right)^{1/2} E^{1/2} \left( \frac{8ma^2}{h^2} \right) dE \end{aligned}$$

$$N(E) dE = \frac{\pi}{4} \left( \frac{8ma^2}{h^2} \right)^{3/2} E^{1/2} dE \quad \dots(9)$$

# Density of States

- Pauli's exclusion principle states that two electrons of opposite spins can occupy each state. Hence, the number of energy states available for electron occupancy is given by

$$\begin{aligned} N(E) dE &= 2 \times \frac{\pi}{4} \left[ \frac{8ma^2}{h^2} \right]^{3/2} E^{1/2} dE \\ &= \frac{\pi}{2} \frac{(8m)^{3/2}}{(h^2)^{3/2}} (a^2)^{3/2} E^{1/2} dE \\ &= \frac{\pi}{2} (8m)^{3/2} \left( \frac{a^3}{h^3} \right) E^{1/2} dE \\ N(E) dE &= \frac{\pi}{2} \left( \frac{a^3}{h^3} \right) (8m)^{3/2} E^{1/2} dE \quad \dots (10) \\ (8m)^{3/2} &= (8m)^1 (8m)^{1/2} \\ &= 4 \times 2m (4 \times 2m)^{1/2} \\ &= 4 \times (2m)^1 (2^2 \times 2m)^{1/2} \end{aligned}$$

# Density of States

$$\begin{aligned} &= 4 \times 2 \times (2m)^{3/2} \\ &= 8 (2m)^{3/2} \\ N(E) dE &= \frac{\pi}{2} \left( \frac{a^3}{h^3} \right) 8 (2m)^{3/2} E^{1/2} dE \end{aligned}$$

$$= \frac{\pi a^3}{h^3} 4 (2m)^{3/2} E^{1/2} dE$$

$$N(E) dE = \frac{4\pi}{h^3} a^3 (2m)^{3/2} E^{1/2} dE \quad \dots (11)$$

- Density of states is given by the number of energy states per unit volume.
- on substituting for  $N(E) dE$  and  $V$ , we have, Density of states:

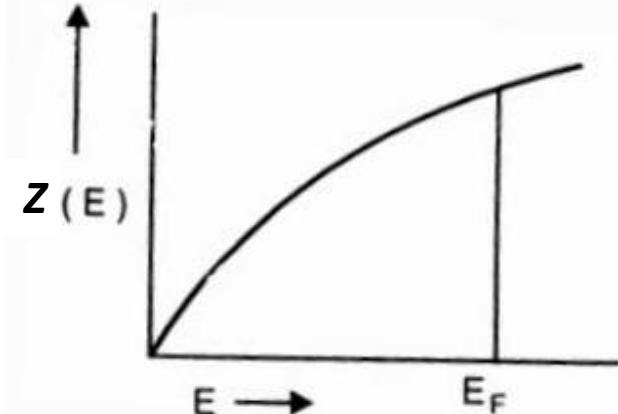
$$Z(E) dE = \frac{N(E) dE}{V} \quad \dots (12)$$

# Density of States

$$Z(E) dE = \frac{\frac{4\pi}{h^3} a^3 (2m)^{3/2} E^{1/2} dE}{a^3} \quad [\because \text{Volume } V = a^3]$$

$$Z(E) dE = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} dE$$

...(13)



- The above eqn. can also be written as follows:

$$z(E) = \frac{1}{2\pi^2} \left( \frac{2m}{\hbar^2} \right)^{\frac{3}{2}} E^{\frac{1}{2}}$$

- This is the expression for the density of states in energy between  $E$  and  $E + dE$ .
- It is used to calculate carrier concentration in metals and semiconductors.
- Density of states is a continuous function of energy in case of conductors.
- In case of semiconductors, it is not continuous as there is a band gap.
- Variation of density of states as a function of energy is different in valence band and in conduction band and this affects the position of Fermi energy level in intrinsic and extrinsic semiconductors.

# Density of States in Semiconductor

- Density of states for a free electron is given by:

$$z(E) = \frac{1}{2\pi^2} \left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}} \quad \dots(1)$$

- In the above eqn.  $E$  is the energy of free electron given by,

$$E = \frac{\hbar^2}{2m} k^2 \quad \dots(2)$$

- When electron is in conduction band, the equation of its energy is given by,

$$E - E_c = \frac{\hbar^2}{2m} k^2 \quad \dots(3)$$

- Therefore, replacing  $E$  by  $E - E_c$  in eqn. (1), we get,

$$z(E) = \frac{1}{2\pi^2} \left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} \quad \dots(4)$$

- Eqn. (4) gives the density of states in conduction band.

# Density of States in Semiconductor

- When electron is in valence band, the equation of its energy is given by,

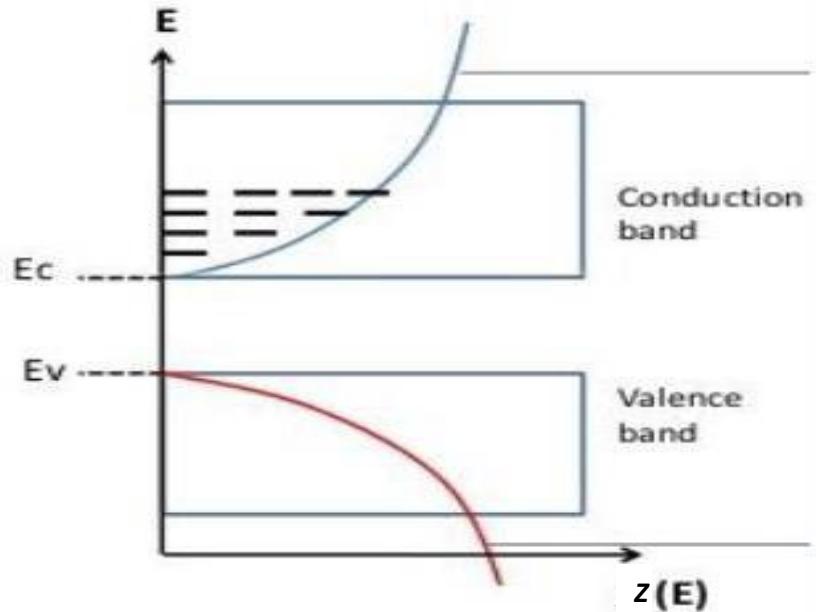
$$E_V - E = \frac{\hbar^2}{2m} k^2 \quad \dots(5)$$

- Therefore, replacing  $E$  by  $E_V - E$  in eqn. (1), we get,

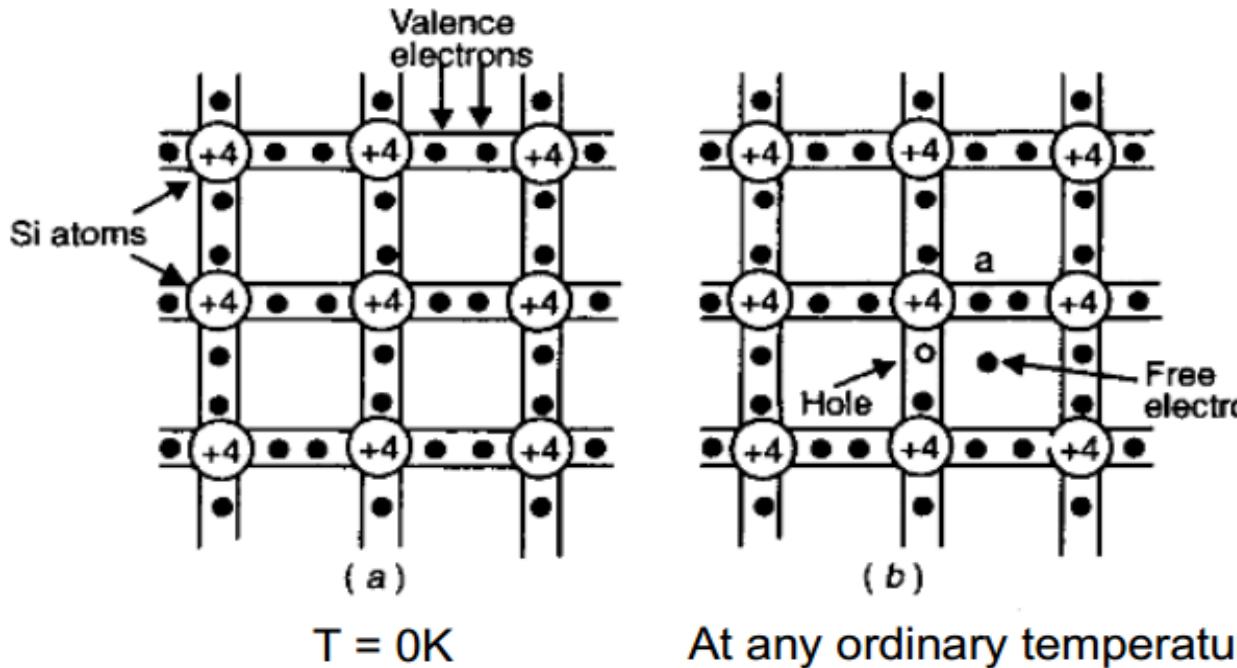
$$z(E) = \frac{1}{2\pi^2} \left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} \quad \dots(6)$$

- Eqn. (6) gives the density of states in valence band.

**Density of state**

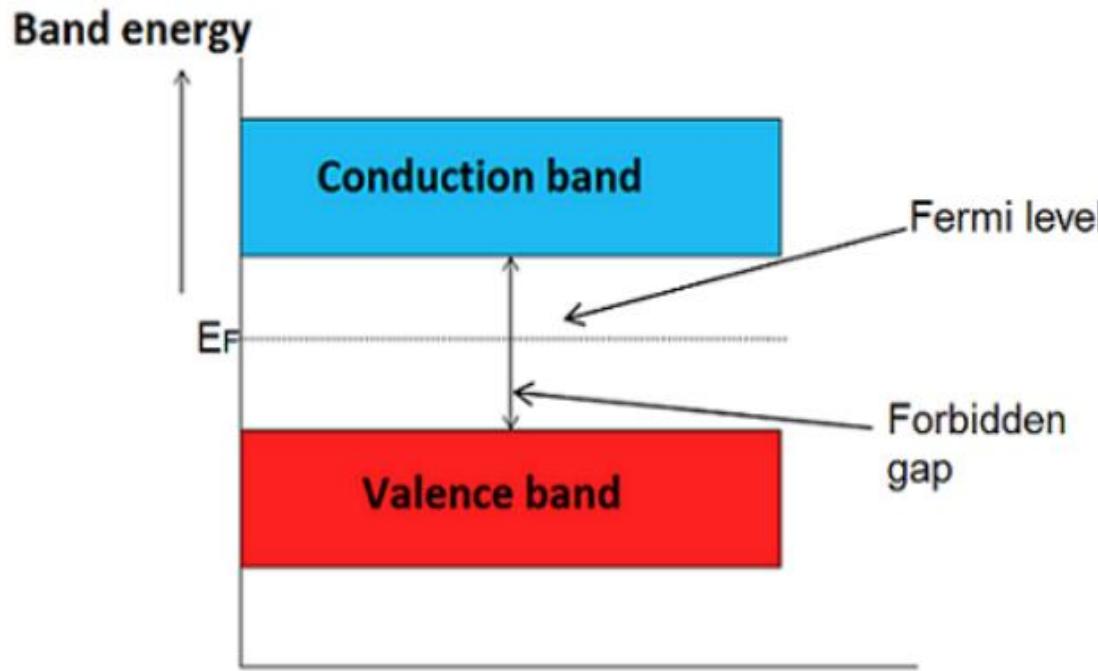


# Fermi Level in Intrinsic Semiconductors



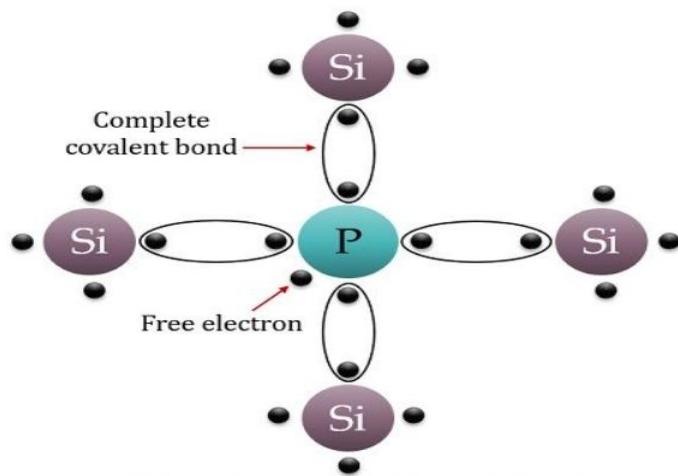
- Each silicon atom has four valence electrons and can form four covalent bonds with four neighboring silicon atoms. At  $T = 0\text{K}$ , no electron is free to cause conduction.
- As temperature increases above  $0\text{K}$ , some of the electrons acquire sufficient thermal energy to break covalent bonds and become free. These electrons move randomly in the crystal, referred as conduction electrons. Each escaped electron leaves an empty space behind called hole, which also act as charge carrier.

# Fermi Level in Intrinsic Semiconductors



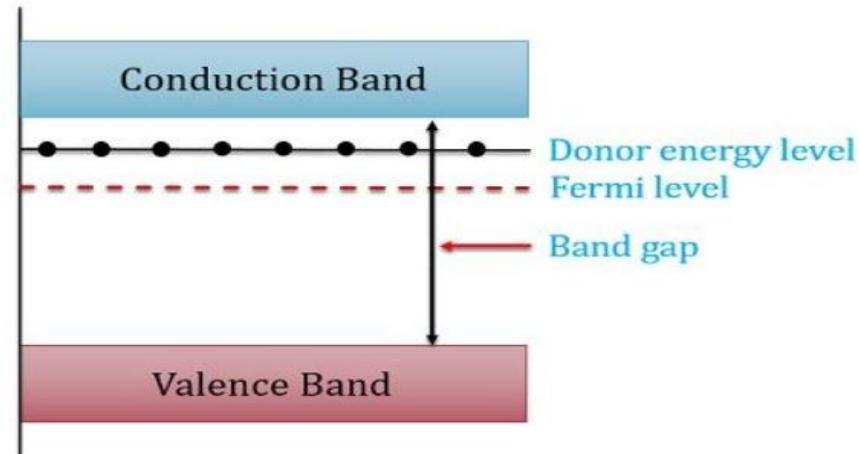
- An electron-hole pair is generated. In intrinsic semiconductors the number of electrons in conduction band are always equal to the number of holes in valence band ( $n_i = p_i$ ).
- Hence, the probability of occupation of energy levels in conduction band and valence band are equal.
- Therefore, the Fermi level for the intrinsic semiconductor lies in the middle of forbidden band.

# Fermi Level in n-type Semiconductors



- Si = Intrinsic semiconductor atom
- P = Pentavalent impurity atom

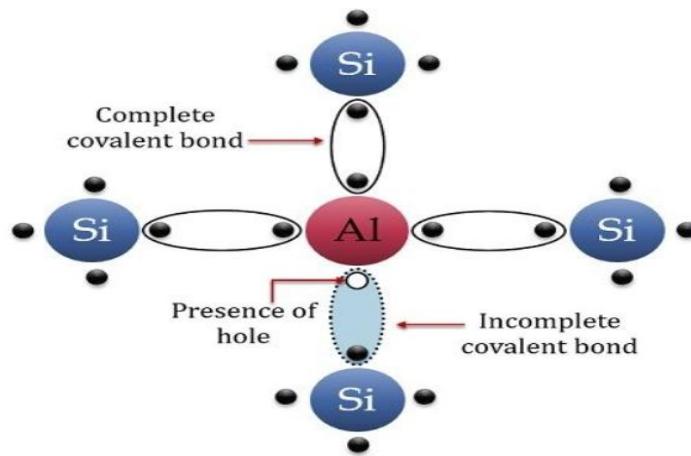
## Formation of N type extrinsic semiconductor



Energy level diagram of  
N type semiconductor

- In n-type semiconductor pentavalent impurity such as Phosphorus, Arsenic or Antimony is added. Each pentavalent impurity donates a free electron. The addition of pentavalent impurity creates large number of free electrons in the conduction band.
- At room temperature, the number of electrons in conduction band is greater than the number of holes in valence band.
- Hence, the probability of occupation of energy levels by the electrons in the conduction band than the probability of occupation of energy levels by the holes in valence band.

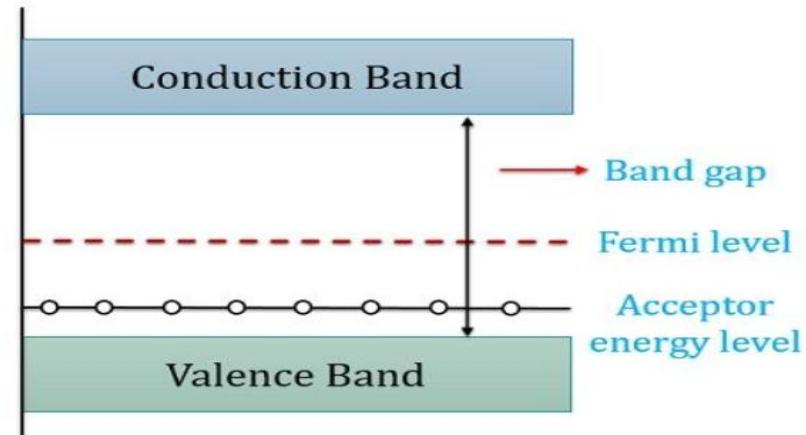
# Fermi Level in p-type Semiconductors



- Si = Intrinsic semiconductor atom
- Al = Trivalent impurity atom

## Formation of P type extrinsic semiconductor

- In p-type semiconductor trivalent impurity such as Boron, Aluminium or Indium is added. Each trivalent impurity introduces a hole in the valence band and ready to accept an electron. The addition of trivalent impurity creates large number of holes in the valence band.
- At room temperature, the number of holes in valence band is greater than the number of electrons in conduction band.
- Hence, the probability of occupation of energy levels by the holes in the valence band than the probability of occupation of energy levels by the electrons in conduction band.

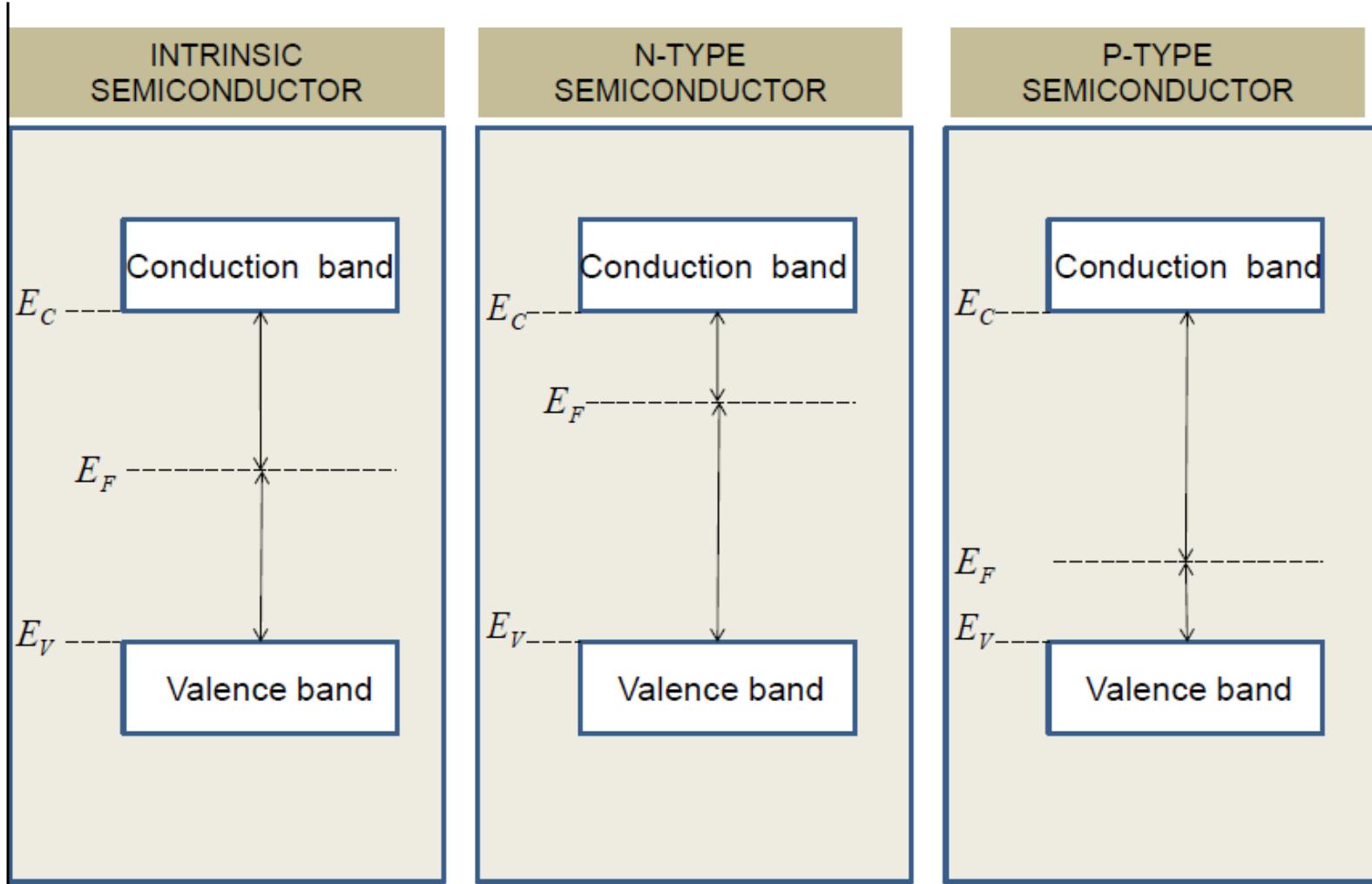


Energy level diagram of  
P type semiconductor

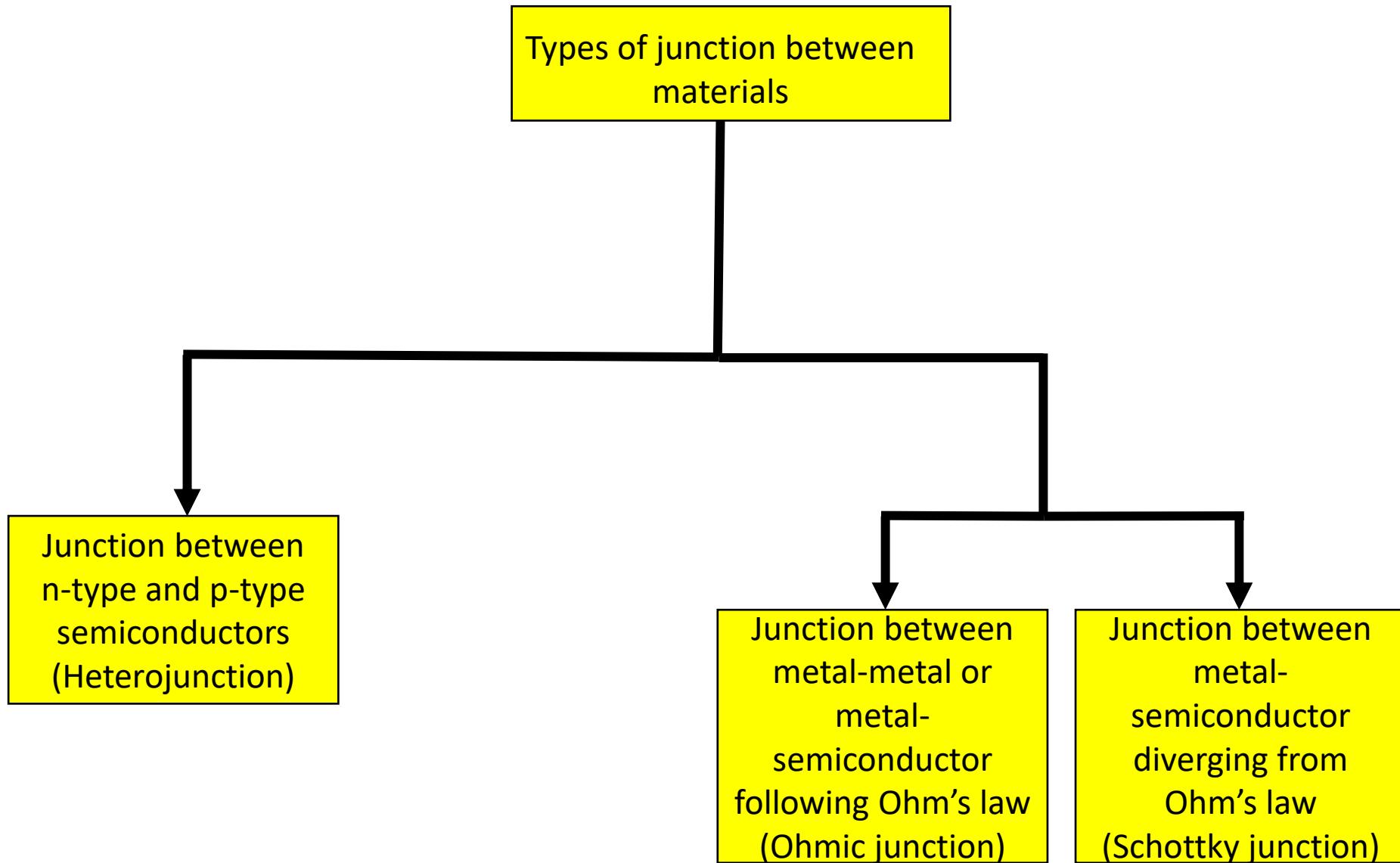
# Position of Fermi level in Semiconductors

- Fermi level position characterizes the material (semiconductor) as intrinsic, n-type and p-type.
- In intrinsic semiconductor the Fermi level lies in the middle of the forbidden gap.
- In n-type semiconductor the Fermi level lies near the conduction band.
- In p-type semiconductor the Fermi level lies near the valence band.
- Position of Fermi level changes when the temperature or doping concentration changes.
- The Fermi level also shifts when the semiconductor is biased.

# Position of Fermi level in Semiconductors



# Junction between two types of materials



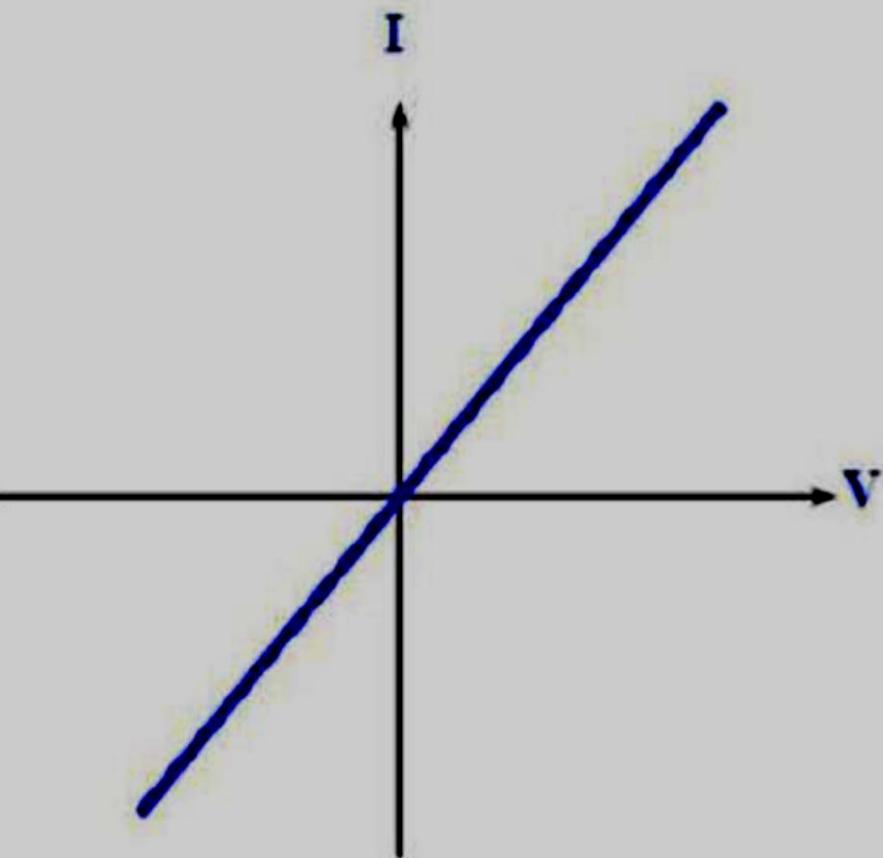
# Metal-Metal junction (Ohmic Junction)

- In a metal-metal junction, both sides of the junction consist of metallic materials.
- These junctions typically exhibit ohmic behavior meaning that the current-voltage (I-V) characteristics are linear and follow Ohm's law ( $I = V/R$ ).
- In an ohmic junction, the resistance (R) remains constant over a wide range of applied voltages.
- This is because metals have a high density of free electrons, and the movement of these electrons is not impeded significantly.
- Therefore, the resistance does not change significantly with the applied voltage.

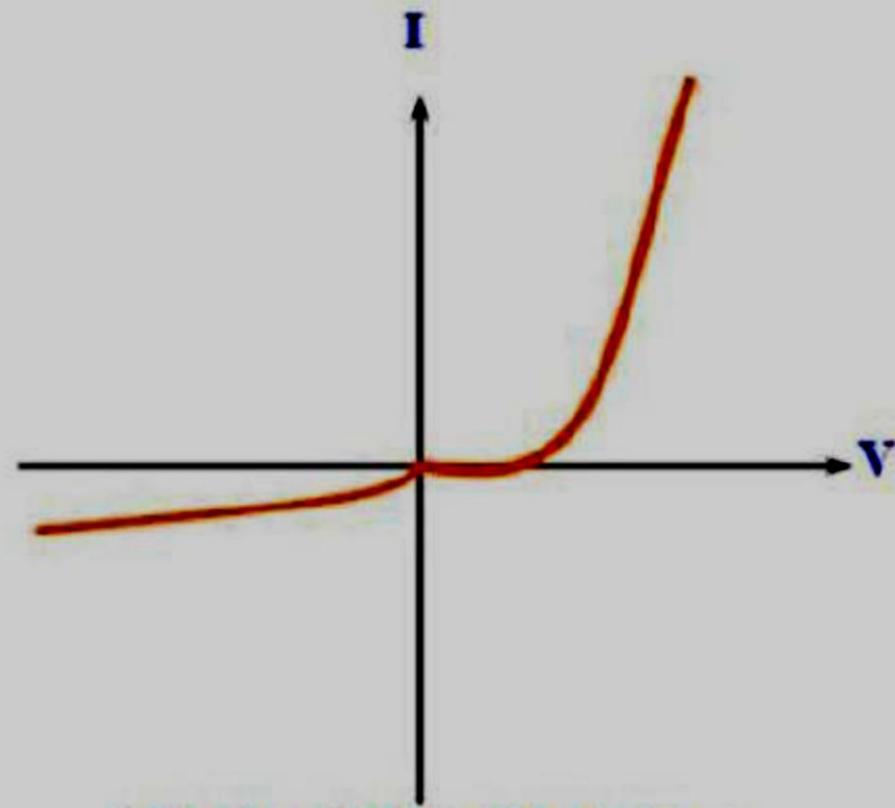
# Metal-Semiconductor junction (Ohmic Junction)

- In a metal-semiconductor junction displaying ohmic behavior the semiconductor material is typically highly doped.
- Doping introduces a large number of charge carriers (either electrons or holes) into the semiconductor.
- When electrons diffuse from a heavily doped semiconductor to a metal, positive ions are produced in n-type semiconductor and negative ions are produced in metal.
- But metal and n-type semiconductor both have high density of states. Atoms from narrow n-type will loose and atoms from narrow metal will gain electrons.
- Because of this, a very narrow depletion region is formed on both sides. Overall depletion region is extremely narrow so the potential barrier height is also very less; hence the electrons can easily overcome the barrier, and it does not have rectifying capability.
- The I-V characteristics of an ohmic metal-semiconductor junction remain linear, and the resistance is relatively constant.

# I-V curves of Ohmic and Schottky junctions



Ohmic contact I-V.



Schottky I-V just look like a  
pn diode I-V.

# Metal-Semiconductor junction (Schottky Junction)

## Schottky junction:

- The atoms from wider region of N-type semiconductor will lose electrons and the atoms from narrow region of metal will gain electrons. Hence positive ions are produced in n-type semiconductors and negative ions in metal.
- Metals usually have high density of states (no. of available states per unit volume) and hence more electrons can be accommodated in less volume. Hence, atoms from wider n-type semiconductor will lose electrons and atoms from narrower regions of metal will gain electrons.
- Therefore, the depletion region is thick within n-type semiconductor and negligibly thin within the metal.
- Because of the depletion region, a potential barrier is developed across the junction which is sufficiently high so that electrons cannot overcome this barrier.
- When external voltage source is connected in forward bias, this barrier height will decrease and the current will be conducted through the junction whereas under reverse bias, this barrier height will increase and the current will not be conducted through the junction.
- Hence this junction show rectifying behavior.

# References

- Solid State Physics, R. K. Puri and V. K. Babbar
- Engineering Physics, H. K. Malik and A. K. Singh

# THANK YOU...!!!