18PYB103J -UNIT 1

Physics: Semiconductor Physics (SRM Institute of Science and Technology)

18PYB103J - Semiconductor Physics

UNIT - I

Classical free electron theory - Quantum free electron theory - Density of states - Energy band in solids - Kronig-Penney model - 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.

Free electron theory of solids :-

Characteristics :-

The electron theory of solids explains the structure and properties of solids through their electronic structure. The theory is applicable to both solids and non-solids.

Different theories available :-

- Classical free electron theory (Drude and Lorentz free electron theory)

- Quantum free electron theory (Sommerfeld quantum theory)
- Band theory of solids.

Classical free electron theory :-

Principle :- Metal consists of a large number of free electrons, which can move freely throughout the volume of the metal. These free electrons are responsible for the electrical conduction in metals.

Assumptions :-

- Electrons in the inner shell as core electrons and outermost shell called as valence electrons.
- Free or conduction electrons : Valence electrons get detached and move freely in the volume of metals.
- Free electron gas : Drude assumed that free electrons in a metal form electron gas where random motion of electrons is comparable to the motion of gas molecules in a container.

- Electric field: Absent : Electrons move in random manner in metal, collide with other electrons and positive ion core, leading to elastic collisions.
- Electric field: Present: Electrons acquire some energy and move towards positive potential

Important terms:-

- Drift velocity: (v_d)

The average velocity acquired by the free electrons of a metal in a particular direction by the application of an electric field.

- Mean free path: (λ)

Average distance travelled by a free electron between any two successive collisions in the presence of an applied electric field.

- collision time :: (τ_c)

Average time taken by a free electron between any two successive collisions.

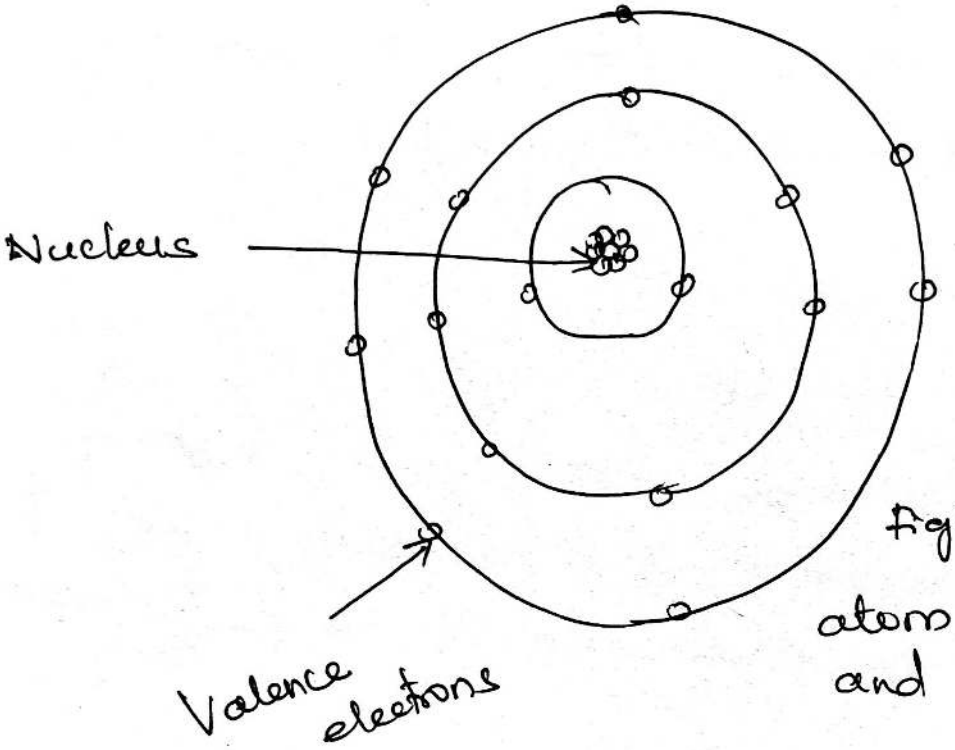
- Relaxation time :- (τ)

Average time taken by a free electron to reach its equilibrium position from its disturbed position due to the

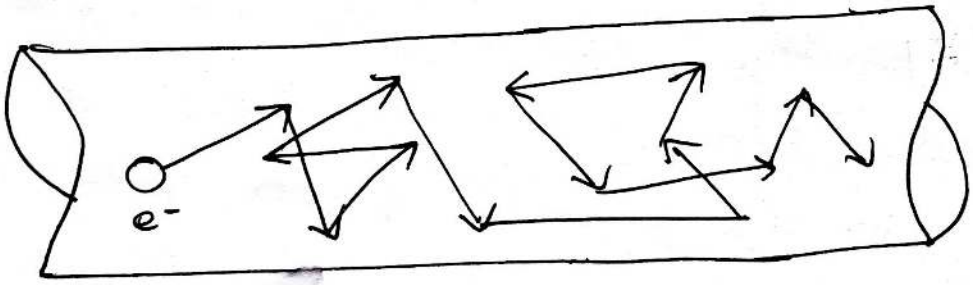
application of an external electric field.

Demerits:

- Contradiction in the absorption of energy from supplied energy.



fig(i) Shell structure of atom with inner electrons and valence electrons.



Fig(ii) Electron motion in an applied electric field

- failure of explanation for the properties of non-metals.
- failure to explain the concept of photoelectric effect, compton effect and blackbody radiation, specific heat of solids.
- Failure to explain the temperature dependence of electrical conductivity.

Quantum free electron theory

Definition: This theory uses the concepts and assumptions from quantum mechanics and hence it is known as quantum free electron theory.

Assumptions:

- Potential of an electron is uniform or same inside the crystal.
- Wave nature is exhibited by the electrons inside the crystal.
- Quantization of allowed energy levels of electrons.
- Electrons are free to move within the crystal and are restricted from leaving the crystal due to potential barrier at the surface.
- Fermi - Dirac statistics is applicable for electrons
- Obeys Pauli's exclusion principle.

Merits:

- Treatment of electrons according to quantum mechanics.
- Explanation of electrical conductivity, thermal conductivity and specific heat capacity of metals.

- Explanation for the photoelectric effect and compton effect.

Demerits:

- This theory explains most physical properties of metals, but fails to differentiate metals, semiconductors and insulators.
- Fails to explain the positive value of Hall coefficient
- Fails to explain some of the transport properties of metals.

De broglie wavelength :- $\lambda = h/p$

Schroedinger wave equation

- It is one of the basic equation in Quantum mechanics
- It is used to describe the dual nature of matter waves.
- It is applicable for both microscopic and macroscopic particles.

Schroedinger Time-independent wave equation

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

for 1D motion $\Rightarrow \frac{d^2\psi}{dx^2} + \frac{8\pi^2 m}{h^2}(E-V)\psi = 0$

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

for 3D, $\nabla^2\psi + \frac{2m}{\hbar^2}(E-V)\psi = 0$

Schroedinger time dependent wave equation

$$-\frac{\hbar^2}{2m}\cdot\nabla^2\psi + V\psi = i\hbar\frac{\partial\psi}{\partial t}$$

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)\psi = i\hbar\frac{\partial\psi}{\partial t}$$

(or) $\quad H\psi = E\psi$

$H = -\frac{\hbar^2}{2m}\nabla^2 + V \rightarrow$ Hamiltonian Operator

$E = i\hbar\frac{\partial}{\partial t} \rightarrow$ Energy operator

Density of States: $Z(E)\,dE$

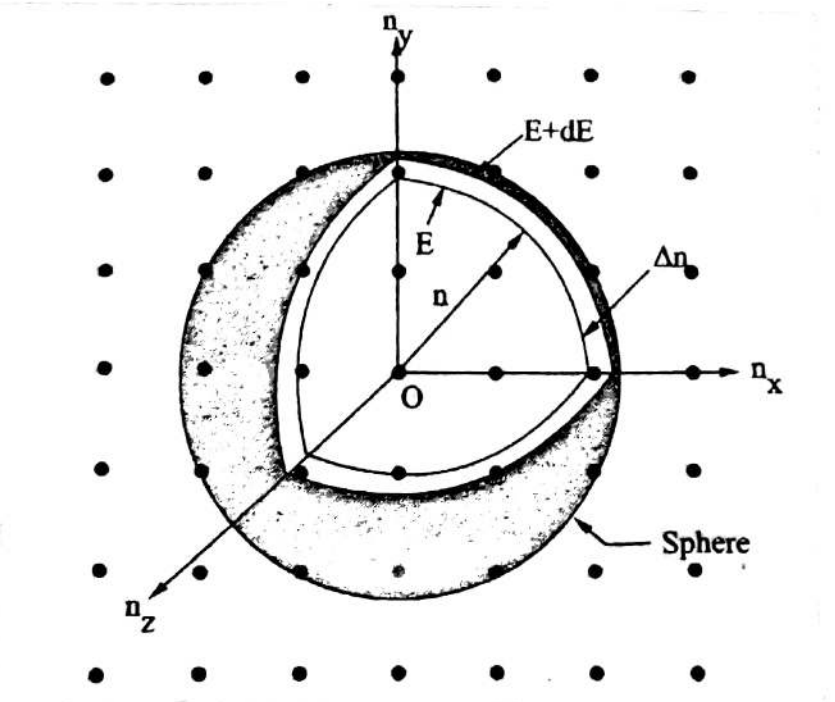
. The density of states is defined as the number of available electron states per unit volume in an energy interval E and E + dE.

Let us consider a metal piece of side 'l'. To find the density of states, construct a sphere of radius 'n' in the space as shown in diagram. The sphere is further divided into many shells corresponding to quantum numbers n_x, n_y and n_z.

We consider two energy levels having values 'E' and E + dE, corresponding to the quantum numbers n and n + dn.

$$\left.\begin{array}{l}\text{The no. of states within sphere}\\ \text{of radius } n\end{array}\right\} = \frac{4}{3}\pi n^3 \longrightarrow (1)$$

we take only $\frac{1}{8}$ of volume of sphere. because the quantum numbers are positive values.



$\therefore$ Eq (1) becomes,

The no. of states within the sphere of radius 'n' $= \frac{1}{8}\left[\frac{4}{3}\pi n^3\right] \rightarrow (2)$

The no. of states within the sphere of radius 'n' and n+dn $= \frac{1}{8}\left[\frac{4}{3}\pi (n+dn)^3\right] \rightarrow (3)$

The no. of states between the shells of radius n and n+dn $= \frac{1}{8}\frac{4}{3}\pi\left[(n+dn)^3 - n^3\right]$

$$= \frac{\pi}{6}\left[n^3 + 3n^2 dn + 3n dn^2 + dn^3 - n^3\right]$$

$$= \frac{\pi}{6_2}\left[3n^2 dn\right]$$

$$= \frac{\pi}{2}(n)(n dn) \rightarrow (4)$$

No of states $= \frac{\pi}{2}(n)(n dn)$

The energy of the electron moving in a cubical metal piece of side 'l' is given by,

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

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

$$n = \left(\frac{8ml^2}{h^2}\right)^{1/2} E^{1/2} \rightarrow (6)$$

Differentiating eqn (5) w.r.t 'E'

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

$$n\,dn = \frac{1}{2}\left(\frac{8ml^2}{h^2}\right)dE \longrightarrow (7)$$

Substitute eqn (6) and (7) in eqn (4) we get,

$$\text{No of States} = \frac{\pi}{2}\left(\frac{8ml^2}{h^2}\right)^{1/2} E^{1/2}\,\frac{1}{2}\left(\frac{8ml^2}{h^2}\right)dE$$

$$\text{No of States} = \frac{\pi}{4}\left(\frac{8ml^2}{h^2}\right)^{\frac{3}{2}} E^{1/2}\,dE$$

$$\text{No of States} = \frac{\pi}{4}\left(\frac{8m}{h^2}\right)^{3/2} l^3\, E^{1/2}\,dE$$

$$\frac{\text{No of States}}{l^3} = \frac{\pi}{4}\left(\frac{8m}{h^2}\right)^{3/2} E^{1/2}\,dE$$

Density of States $Z(E)\,dE = \frac{\pi}{4}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} E^{1/2}\,dE$

Acc. to Pauli's exclusion principal,

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

$$\boxed{Z(E)\,dE = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}}\,dE} \longrightarrow (8)$$

Carrier Concentration in metals: $N(E)\,dE$

The number of electrons in the filled energy states between the energy intervals E and $E+dE$ is given by,

$$N(E)\,dE = Z(E)\,dE \cdot F(E)$$

$$N(E)\,dE) = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{3/2} E^{1/2}\,dE \cdot F(E)$$

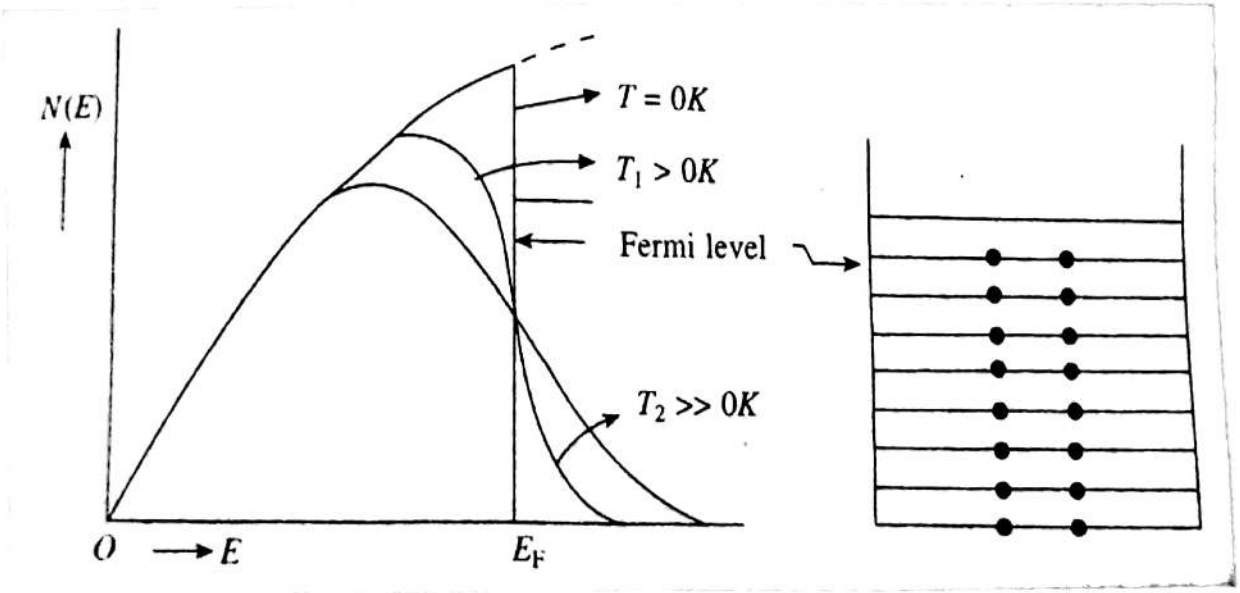
The Fermi energy of electrons at $T = 0k$:

When $T = 0k$; $F(E) = 1$

$$\therefore \int_0^N dN = \int_0^{E_{F_0}} \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{3/2} E^{1/2}\,dE$$

$$N = \frac{\pi}{3h^3}(8m)^{3/2} E_{F_0}^{3/2}$$

$$\boxed{E_{F_0} = \frac{h^2}{8m}\left(\frac{3N}{\pi}\right)^{\frac{2}{3}}}$$



Electrons in periodic potential: Zone theory / Band theory:

In quantum free electron theory, the electrons are assumed to move in constant potential. But it failed to explain why some solids behaves as conductors, some as insulators and some as semiconductors.

Therefore, instead of considering an electron to move in a constant potential, In band theory of solids the electrons are assumed to move in a field of Periodic potential.

In a metal, the positive ions are arranged in a regular manner. so the potential field varies periodically. The potential is minimum near the centre of the positive ions and maximum between the centres of ~~dits~~ ions.

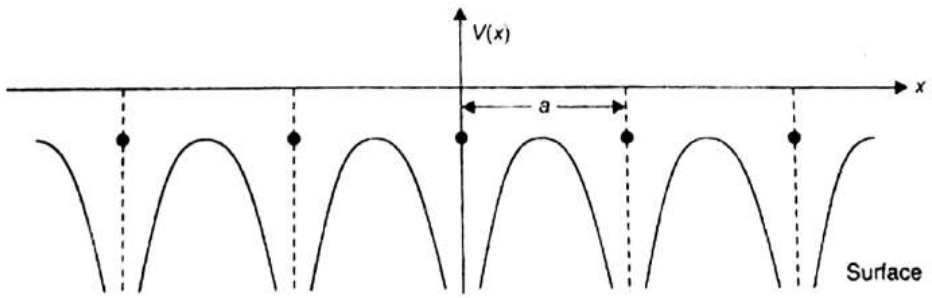


FIGURE **11.4 Representation of potential experienced by an electron in a perfectly**

Bloch theorem:

Bloch theorem is a mathematical statement of an electron wave function moving in a perfectly periodic potential.

Let us consider an electron moving in a periodic potential. the wave equation is given by

$$\frac{d^2\psi(x)}{dx^2} + \frac{2m}{\hbar^2}(E - V(x))\psi(x) = 0 \quad \rightarrow (1)$$

Since the electron ~~has~~ is moving along x - direction The potential energy of electron should satisfy the condition $V(x) = V(x+a)$, where 'a' is the periodicity of potential.

The solution of eqn (1) is

$$\psi(x) = e^{ikx} u_k(x) \quad \rightarrow (2)$$

where $u_k(x)$ represents the periodic function.

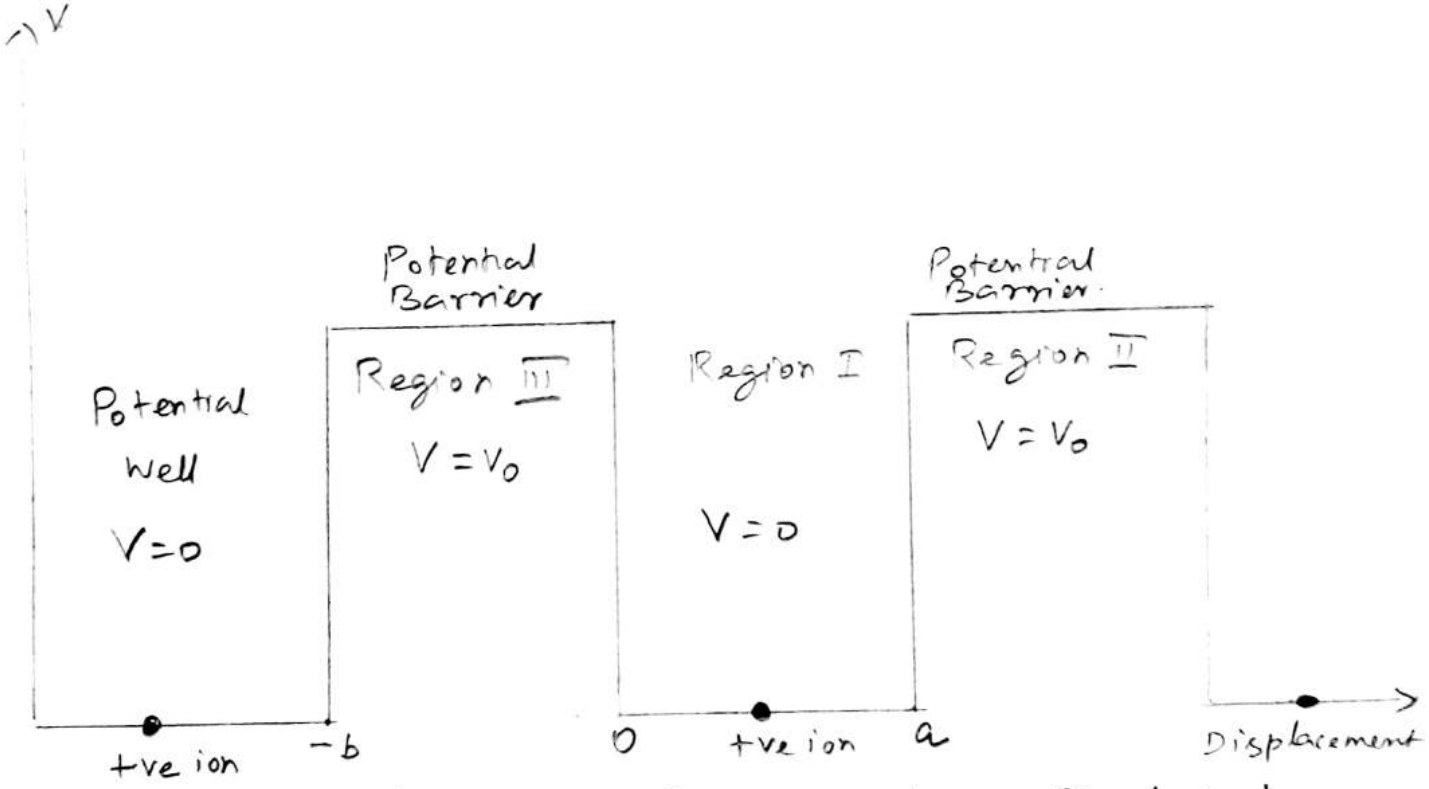
$$u_k(x) = u_k(x+a) \quad \rightarrow (3)$$

where e^{ikx} represents the plane wave.

Eqn. (2) is called as Bloch theorem and eqn (3) is called Bloch function.

Kronig - Penny Model:

Kronig - Penny model illustrates that the electrons move in a periodic potential produced by the positive ion cores in the metal. The potential of the electron varies periodically with periodicity of ion core and the potential energy of the electron is zero near the positive ion core and maximum when it is present between the adjacent ion core which are seperated by the interatomic spacing 'a'.



The Schrödinger's time independant wave equation is given by

$$\frac{d^2\psi}{dx^2} + \frac{8\pi^2 m}{h^2}(E - V)\psi = 0 \quad \rightarrow (1)$$

In region I, $0 < x < a$, the potential $V = 0$.
So the electron is assumed to be a free particle.

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

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

$$\frac{d^2\psi}{dx^2} + \alpha^2 \psi = 0 \longrightarrow (1)$$

where $$\alpha^2 = \frac{8\pi^2 m}{h^2} E \longrightarrow (1a)$$

In region II, $-b < x < 0$, the potential $V = V_0$

Eqn (1) $\Rightarrow$ $$\frac{d^2\psi}{dx^2} + \frac{8\pi^2 m}{h^2}(E - V_0)\psi = 0$$

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

$$\frac{d^2\psi}{dx^2} - \beta^2 \psi = 0 \longrightarrow (2)$$

where $$\beta^2 = \frac{8\pi^2 m}{h^2}(V_0 - E) \longrightarrow (2a)$$

According to Bloch' theorem, the solution of eqn (1) and eqn. (2) is given by

$$\psi(x) = e^{ikx} u_k(x) \longrightarrow (3)$$

[where k is wave vector $k = \frac{2\pi}{\lambda}$]

By differentiating eqn (3) w.r.to 'x'

$$\frac{d\psi}{dx} = e^{ikx} \frac{du_k}{dx} + u_k e^{ikx} ik$$

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

$$\frac{d^2\psi}{dx^2} = e^{ikx} \frac{d^2u_k}{dx^2} + 2ik\, e^{ikx} \frac{du_k}{dx} - k^2 e^{ikx} u_k \longrightarrow (4)$$

Substitute eqns (3) and eqn (4) in eqn (1),

$$e^{ikx} \frac{d^2u_k}{dx^2} + 2ike^{ikx} \frac{du_k}{dx} - k^2 e^{ikx} u_k + \alpha^2 e^{ikx} u_k = 0$$

$\div e^{ikx} \Rightarrow$

$$\boxed{\frac{d^2u_k}{dx^2} + 2ik \frac{du_k}{dx} + (\alpha^2 - k^2) u_k = 0} \longrightarrow (5)$$

Substitute eqns (3) and eqn (4) in eqn (2),

$$\boxed{\frac{d^2u_k}{dx^2} + 2ik \frac{du_k}{dx} - (\beta^2 + k^2) u_k = 0} \longrightarrow (6)$$

The general solutions of eqn (5) is

$$U_1 = A e^{i(\alpha-k)x} + B e^{-i(\alpha+k)x} \quad \rightarrow (7)$$

where $U_1 = u_k$ in $0 < x < a$

The general solutions of eqn (6) is

$$U_2 = C e^{(\beta-ik)x} + D e^{-(\beta+ik)x} \quad \rightarrow (8)$$

where $U_2 = u_k$ in $-b < x < 0$

For boundary condition: $\left[U_1(x)\right]_{x=0} = \left[U_2(x)\right]_{x=0}$

$$\boxed{A + B = C + D} \quad \longrightarrow (9)$$

For bound. cond.: $\left[\frac{dU_1}{dx}\right]_{x=0} = \left[\frac{dU_2}{dx}\right]_{x=0}$

$$\boxed{i(\alpha-k)A - i(\alpha+k)B = (\beta-ik)C - (\beta+ik)D} \quad \rightarrow (10)$$

For bound. cond.: $\left[U_1(x)\right]_{x=a} = \left[W_2(x)\right]_{x=-b}$

$$\boxed{A e^{i(\alpha-k)a} + B e^{-i(\alpha+k)a} = C e^{-(\beta-ik)b} + D e^{(\beta+ik)b}} \quad \rightarrow (11)$$

For bound. cond.: $\left[\frac{dU_1}{dx}\right]_{x=a} = \left[\frac{dU_2}{dx}\right]_{x=-b}$

$$\boxed{i(\alpha-k)A e^{i(\alpha-k)a} - i(\alpha+k)B e^{-i(\alpha+k)a} = (\beta-ik)C e^{-(\beta-ik)b} - (\beta+ik)D e^{(\beta+ik)b}} \quad \rightarrow (12)$$

(14)

From the equations (9), (10), (11) and (12), the coefficients of A, B, C and D are taken in the form of determinant and it is equated to zero.

The solution of the determinant is given by

$$P\frac{\sin \alpha a}{\alpha a} + \cos \alpha a = \cos ka \quad \rightarrow (13)$$

where $P = \frac{mV_0 ab}{\hbar^2}$ is called the Scattering power of the potential barrier.

(i) when $P = 0$;

Eqn (13) $\Rightarrow$ $\cos \alpha a = \cos ka$

$$\alpha a = ka$$

$$\alpha = k$$

$$\alpha^2 = k^2$$

$$\frac{8\pi^2 m}{h^2} E = k^2$$

$$E = \frac{\hbar^2 k^2}{2m} \qquad \because \hbar = \frac{h}{2\pi}$$

This represents there is no band gap. so the electrons are moving freely.

(iii) When $P = \infty$,

Eqn.(13) $\Rightarrow$ $\frac{\sin \alpha a}{\alpha a} = 0$

$$\sin \alpha a = 0$$

$$\alpha a = n\pi$$

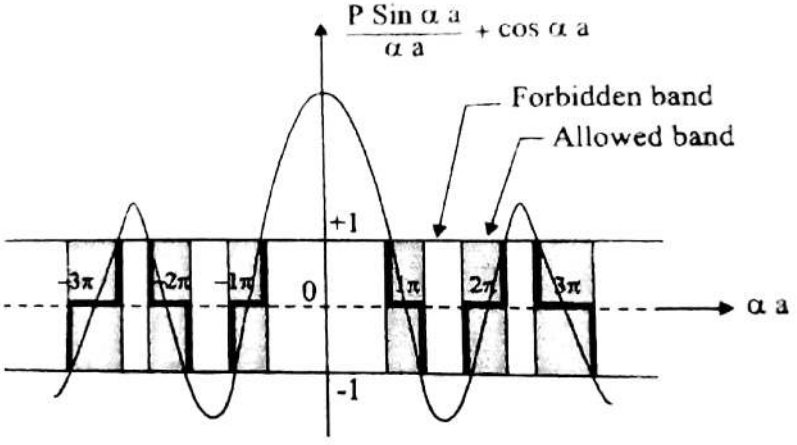
$$\alpha = \frac{n\pi}{a}$$

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

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

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

which represents the electrons will not moving freely so band width decreases



For the value of $P = \frac{3\pi}{2}$ (Arbitrary)

Brillouin Zones:

Brillouin zones are the boundaries marked by the values of $\vec{k}$ in which electrons can have allowed energy values without diffraction.

E-k diagram:

The relation between the wave vector 'k' and the energy 'E' of the electron moving in a potential box of length 'l'.

$$E = \frac{n^2 h^2}{8ml^2} \rightarrow (1)$$

wave vector $k = \frac{n\pi}{l}$

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

$$l^2 = \frac{n^2\pi^2}{k^2} \rightarrow (2)$$

Sub. eqn. (2) in eqn (1)

$$\boxed{E = \frac{k^2 h^2}{8m\pi^2}} \rightarrow (3)$$

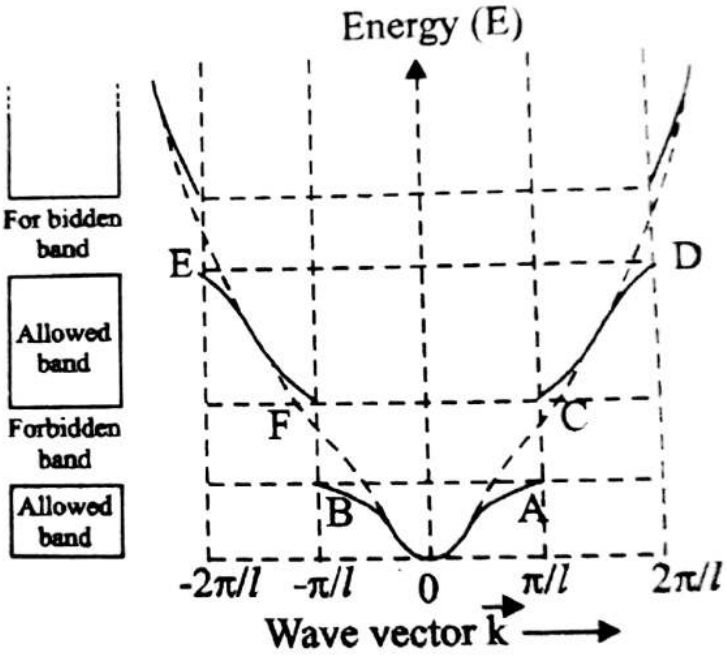
A plot is made between E and k with $n = \pm 1, \pm 2 \ldots$

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

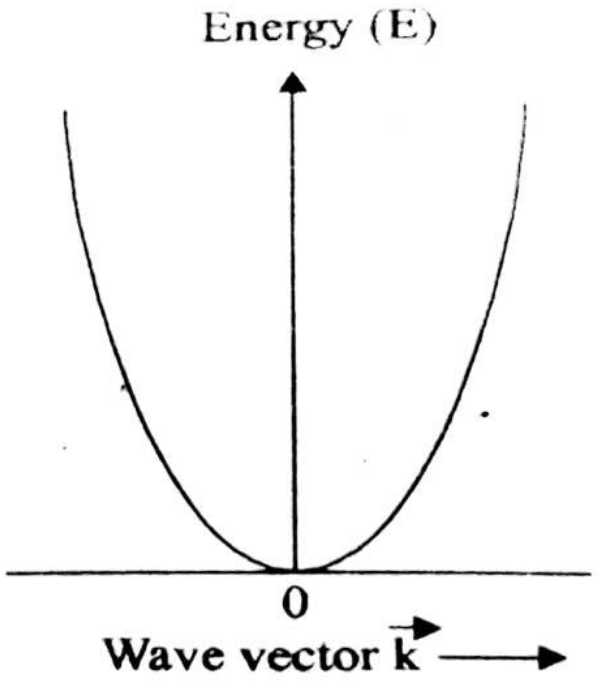
When $n = \pm 1$; $k = \pm \frac{\pi}{l}$

$n = \pm 2$; $k = \pm \frac{2\pi}{l}$

$n = \pm 3$; $k = \pm \frac{3\pi}{l}$



E –k diagram for electron moving in Periodic Potential



E –k diagram for electron moving in constant Potential

In the figure, it is seen that the energy 'E' increases continuously from zero to $\pm \frac{\pi}{l}$. So the electron is moving within the region and is reflected. So this range in called as First Brillioun Zone.

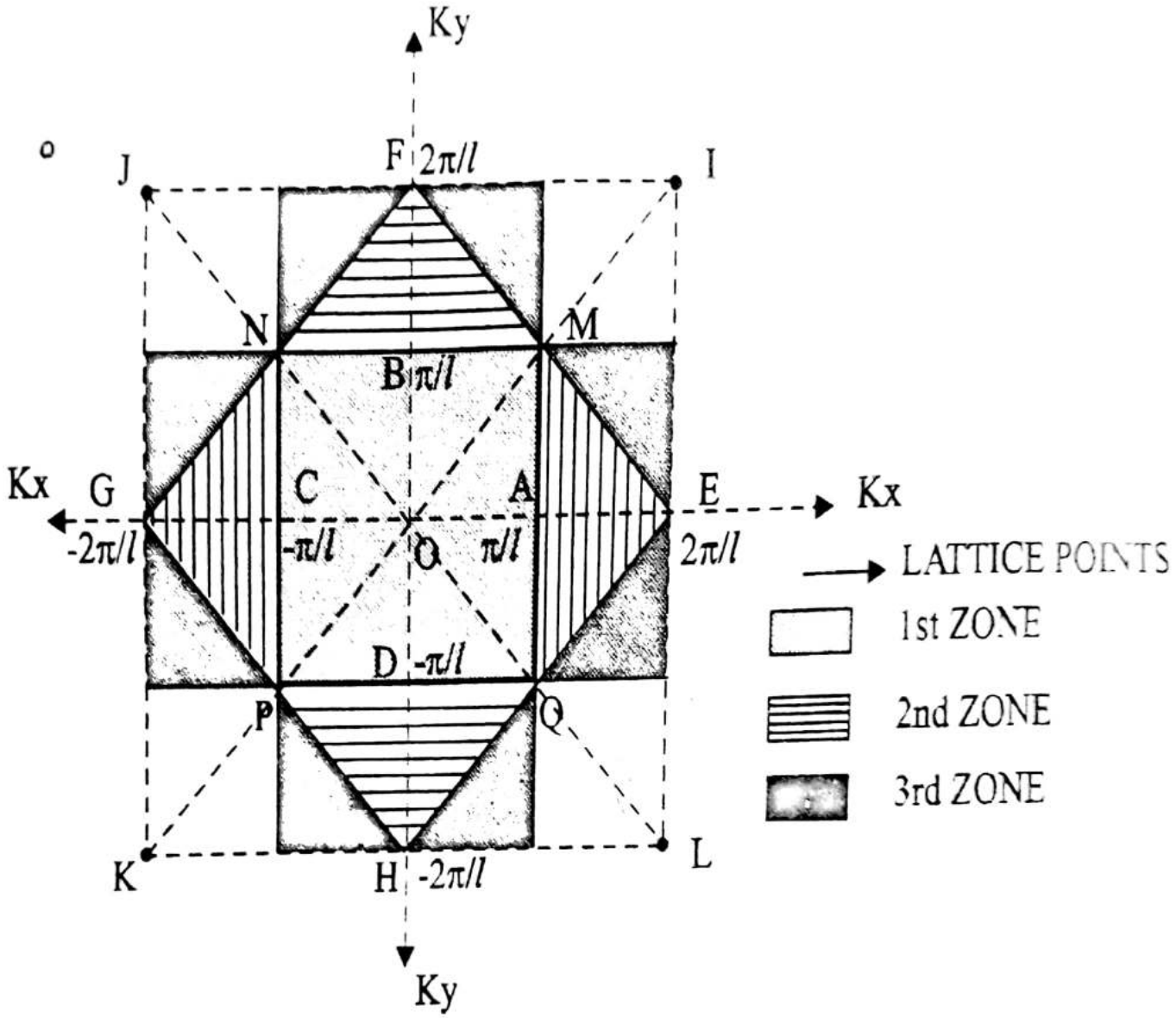
The Second allowed energy values consists of two parts.

$$\frac{\pi}{l} \text{ to } \frac{2\pi}{l} \quad \text{and} \quad -\frac{\pi}{l} \text{ to } -\frac{2\pi}{l}$$

This is called as Second Brillioun Zone.

In the figure, it is noted that each Brillioun Zone is seperated by Forbidden Zone. So the electron can go from one Brillioun Zone to other only if it is supplied with an energy equal to forbidden gap.

So the forbidden gap is one which decides whether the solid is a Conductor / Insulator / Semiconductor.



Brillouin Zone for 2 – dimensional square lattice

(20)

Construction of Brillioun Zone for a 2-dimensional Square lattice:

Let us Consider an electron in the field of 2-D square lattice.

Procedure:

* Take 'O' as the origin and join it to nearest lattice points E, F, G and H.
* Let A, B, C and D are the perpendicular bisectors of OE, OF, OG and OH respectively.
* Join the points ABCD resulting a square is First Brillouin Zone.
* Similarly join the next point I, J, K and L.
* Let M, P, Q and N are ⊥r bisectors of OI, OJ, Ok and OL respectively and Join EFGH.
* The area between EFGH and ABCD gives the Second Brillouin Zone as shown in the figure.

By the same way 3rd, 4th ... etc; Brillouin Zones Can be Constructed.

Effective mass of the electron: m^*

The effective mass of the electron is defined as the mass of the electron, when it is accelerated by applying electric field ($\mathcal{E}$) in a periodic potential.

Consider an electron of mass 'm' moving in a lattice with periodic potential.

The energy of electron $E = \frac{p^2}{2m} \rightarrow (1)$

Where
$p \rightarrow$ Momentum

$\hbar = \frac{h}{2\pi}$

$k = \frac{2\pi}{\lambda} \rightarrow$ wave vector

$$p = \hbar k$$

$$p^2 = \hbar^2 k^2 \rightarrow (2)$$

Sub (2) in (1) $\quad E = \frac{\hbar^2 k^2}{2m} \rightarrow (3)$

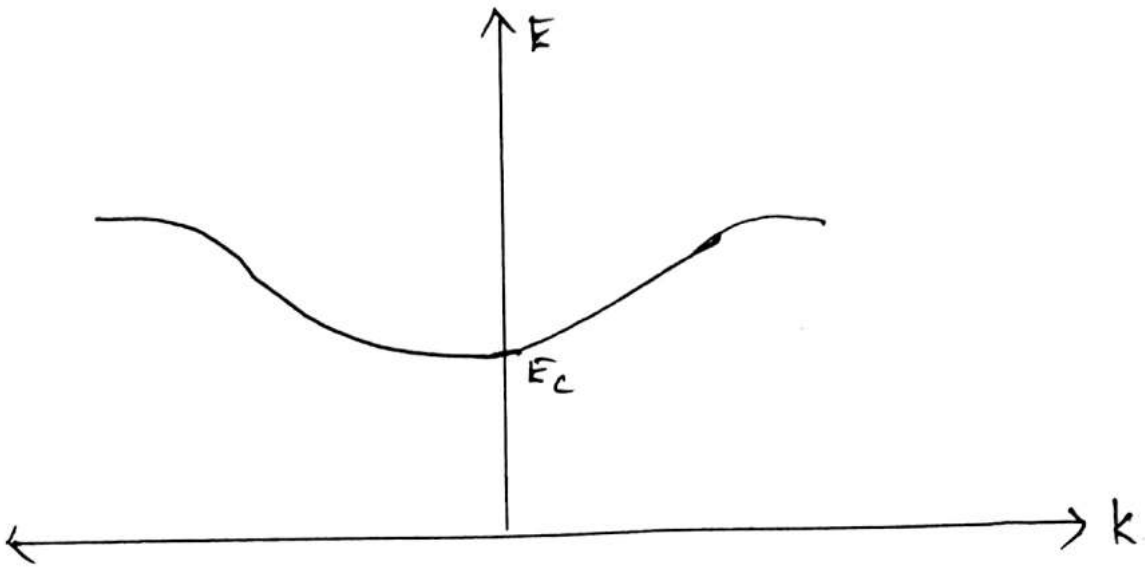
Differentiating Eq (3) w.r.to 'k' twice

$$\frac{1}{\hbar^2}\left(\frac{d^2E}{dk^2}\right) = \frac{1}{m} \rightarrow (4)$$

If we apply electric field $\mathcal{E}$, the electron is accelerated in the opposite direction to $\mathcal{E}$

Force $\quad F = -eE = m^* a$

Now we consider the electron in the bottom of an allowed energy band 'E_c' as shown in Figure.



From graph, $E - E_c = C_1 k^2 \rightarrow (5)$

Differentiate Eq.(5) w.r.t 'k'

$$\frac{dE}{dk} - 0 = C_1 2k$$

Differentiate again, $\frac{d^2E}{dk^2} = C_1 k$

Multiply by $\frac{1}{\hbar^2}$ on both sides

$$\frac{1}{\hbar^2}\left(\frac{d^2E}{dk^2}\right) = \frac{C_1 k}{\hbar^2} \rightarrow (6)$$

Comparing Eqns (4) and (5.)

$$\frac{1}{\hbar^2}\left(\frac{d^2E}{dk^2}\right) = \frac{C_1 k}{\hbar^2} = \frac{1}{m^*}$$

The Effective mass of electron $\Big\}$ $m^* = \dfrac{1}{\frac{1}{\hbar^2}\left(\frac{d^2E}{dk^2}\right)}$

Concept of Phonon:

Any solid crystal consists of atoms bound into a specific repeating three-dimensional spatial pattern called a lattice. Here the atoms behave as if they are connected by tiny springs, their own thermal energy or outside forces make the lattice vibrate. This generates mechanical waves that carry heat and sound through the material. *A packet of these waves can travel throughout the crystal with a definite energy and momentum, so in quantum mechanical terms the waves can be treated as a particle, called a phonon.* A phonon is a definite discrete unit or quantum of vibrational mechanical energy, just as a photon is a quantum of electromagnetic or light energy.

Properties of Phonons:

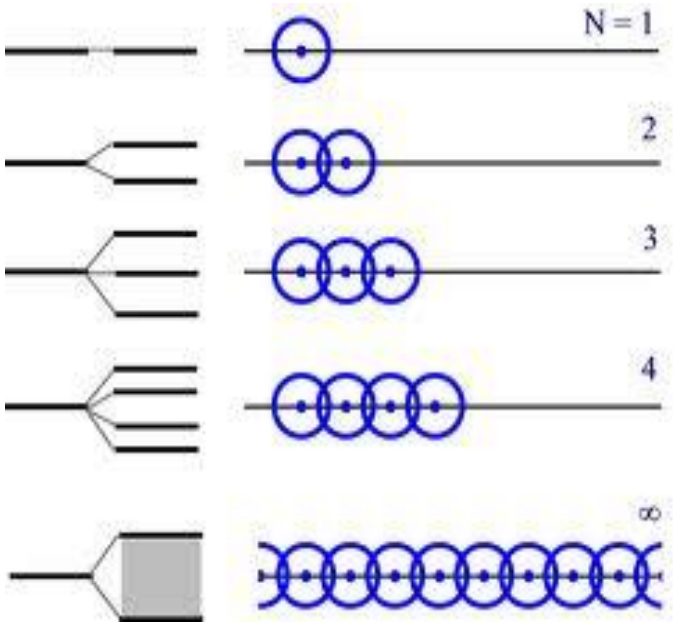
- Energy of phonons is exhibited as thermal energy of solids. The energy of elastic waves of the individual vibrations is $h\nu$.
- At any temperature, the crystal is filled with the gas of phonons. When temperature increases, more phonons are produced.
- Like as light photons, phonons also exhibit wave-particle duality.
- Like sound waves, phonons require a medium to propagate. The medium is the regular arrangement of atoms.
- Vibrational spectrum of the phonon waves has frequency range of 10^4 Hz to 10^{14} Hz. Here the low frequency part is in the acoustic spectrum and the high frequency part is in the infra-red spectrum.

Origin of energy band formation in Solids:

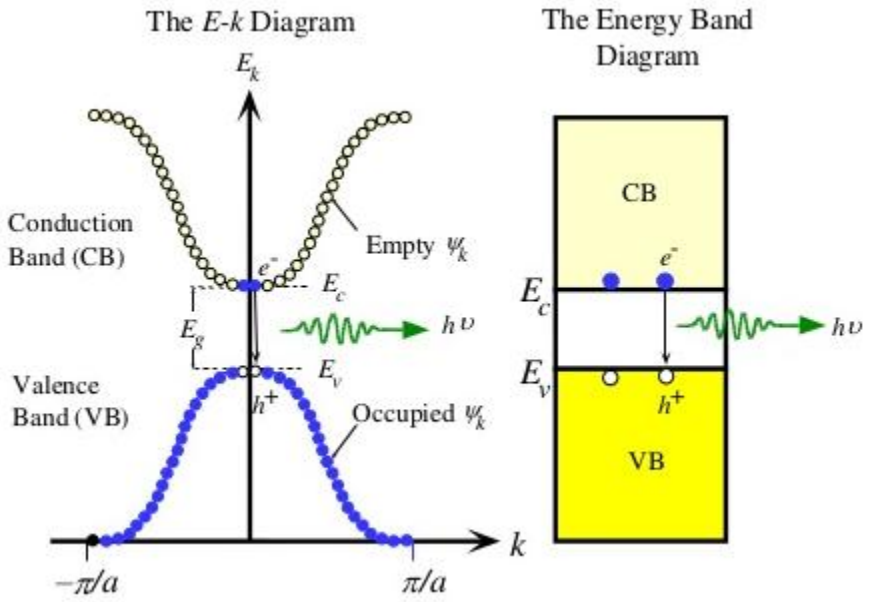
The band theory of solids explains the formation of energy bands and determines whether a solid is a conductor, semiconductor or insulator. The existence of continuous bands of allowed energies can be understood starting with the atomic scale. The electrons of a single isolated atom occupy atomic orbitals, which form a discrete set of energy levels.

When two identical atoms are brought closer, the outermost orbits of these atoms overlap and interact. When the wave functions of the electrons of different atoms begin to overlap considerably, the energy levels corresponding to those wave functions split. If more atoms are brought together more levels are formed and for a solid of N atoms, each of the energy levels of an atom splits into N energy levels. These energy levels are so close that they form an almost continuous band.

The width of the band depends upon the degree of overlap of electrons of adjacent atoms and is largest for the outermost atomic electrons. In solids, the energy band corresponding to the outermost shells are called valence band and the energy formed by conduction levels of various atoms are called conduction band.



In the energy band diagram, conduction band is represented above the valance band. The energy gap between the valance band and the conduction band is known as forbidden energy gap E_g.



Valence band:

A band occupied by valence electrons and is responsible for electrical, thermal and optical properties of solids and it is filled with charge carriers only at temperature 0K.

Conduction band:

A band corresponding to outer most orbits is called conduction band and is the highest energy band and it is completely empty at 0K.

Classification of solids into conductors, semiconductors and insulators:

Based on the energy band diagram materials or solids are classified as follows:

Conductors:

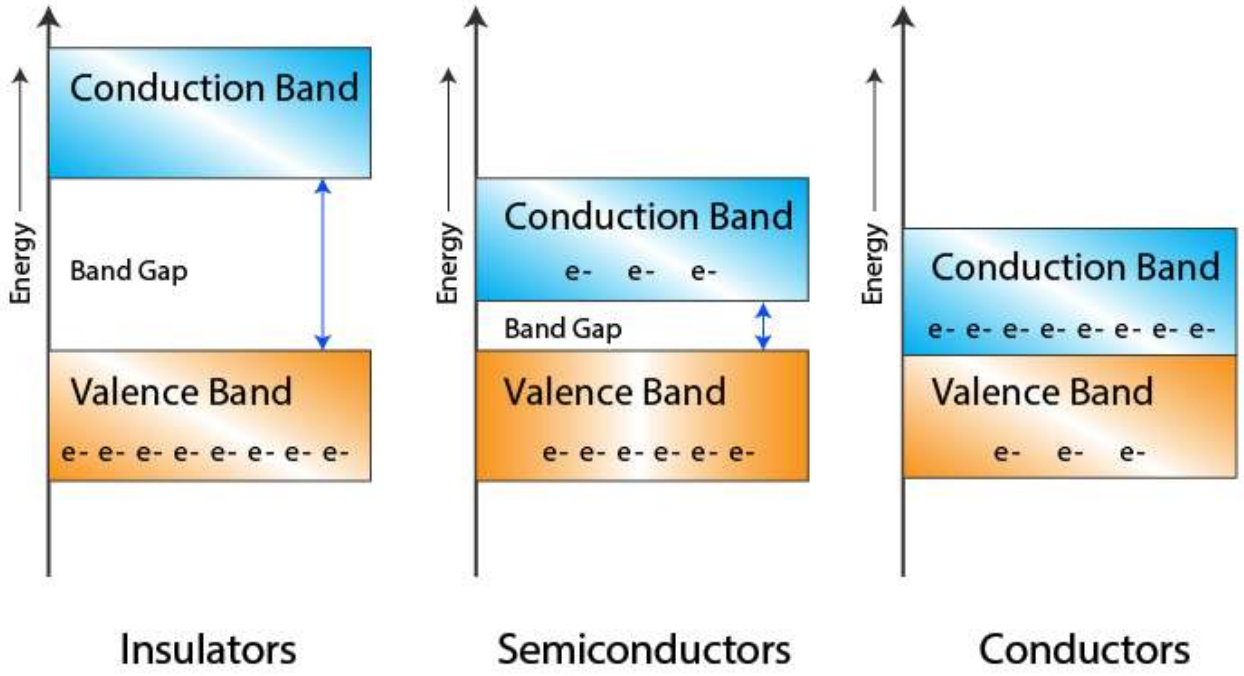
In conductors, there is no forbidden gap between the valence band and conduction band. It is observed that the valence band overlaps with the conduction band in metals. There are sufficient numbers of free electrons, available for electrical conduction and due to the overlapping of the two bands, there is an easy transition of electrons from one band to another band takes place. Resistivity of conductors is very small and it is in the order of 10^{-9} to 10^{-4} Ω m. Examples: Na, Al, Cu, Ni, Cu, Ag, etc.

Semiconductors:

In semiconductors, there is a band gap exists between the valence band and conduction band and it is very less 2 eV are known as semiconductors. It will conduct electricity partially at normal conditions. The electrical resistivity values are moderately high of the order of 10^{-4} to 10^{3} Ω m at room temperature. At higher temperatures, an appreciable number of electrons gain enough energy and are excited across forbidden energy gap. By adding impurities one can increase the electrical conductivity of the semiconductor. Examples: Silicon, Germanium, GaAs.

Insulators:

In insulators, the width of forbidden energy gap between the valence band and conduction band is very large of the order of 3eV to 5.47eV. Due to large energy gap, electrons cannot move from valance band to conduction band. The electrical resistivity of insulators is in the order of 10^{3} to 10^{17} Ω m. Since the electrons are tightly bound to the nucleus, no valence electrons are available. It is estimated that the electrical field in the order of 10^{6} V/m would be required to make the electron to overcome the forbidden gap. Examples: Wood, rubber, glass.



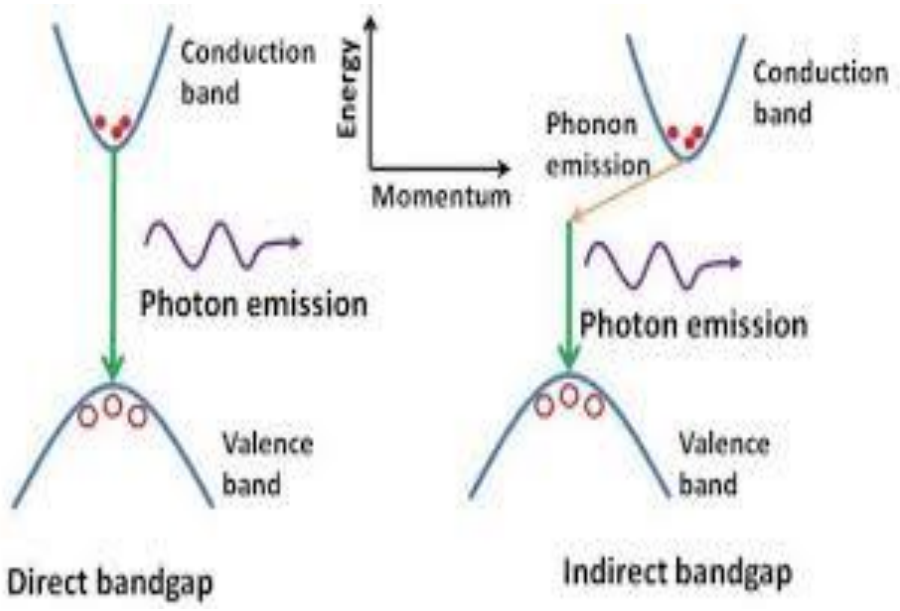
Semiconductors:

The substances whose conductivity lies in between conductors and insulators are called as semiconductors. The properties of semiconductors are given below:

- At temperature 0K, a semiconductor becomes an insulator.
- The electrical conductivity of a semiconductor is increased with increase in temperature.
- The absence of an electron in the valance band of a semiconductor is known as hole. The hole occur only in the valance band.
- Like electrons, the hole in the valance band also conducts electricity in case of a semiconductor.
- The electric current in a semiconductor is the sum of the currents due to electron and hole.

Direct and Indirect band gap semiconductors:

S.No.	Indirect band gap semiconductors (Elemental semiconductors)	Direct band gap semiconductors (Compound semiconductors)
1	They are made of single element from the 4^{th} column of the periodic table. (Ex: Si and Ge)	They are made by combining 3^{rd} and 5^{th} group elements or 2^{nd} and 5^{th} group elements in the periodic table. (Ex: GaAs and InP)
2	Band gap energy is small. For Si, E_g = 0.7 eV For Ge, E_g = 1.12 eV	Band gap energy is comparatively large. For GaAs, E_g = 1.42 eV For InP, E_g = 1.35 eV
3	Electron – hole recombination takes place through traps present in the band gap. So, they are called as Indirect band gap semiconductors.	Electron – hole recombination takes place directly. Therefore, they are called as Direct band gap semiconductors.
4	During recombination process, Phonons are emitted and heat energy is produced.	During recombination process, Photons (light energy) are emitted.
5	Current amplification is more.	Current amplification is less.
6	Life time of charge carriers is more due to indirect recombination.	Life time of charge carriers is less due to direct recombination.
7	Due to the longer life time of charge carriers, these are used to amplify the signals as in the case of diodes and transistors.	They are used to manufacture LEDs and laser diodes etc.,



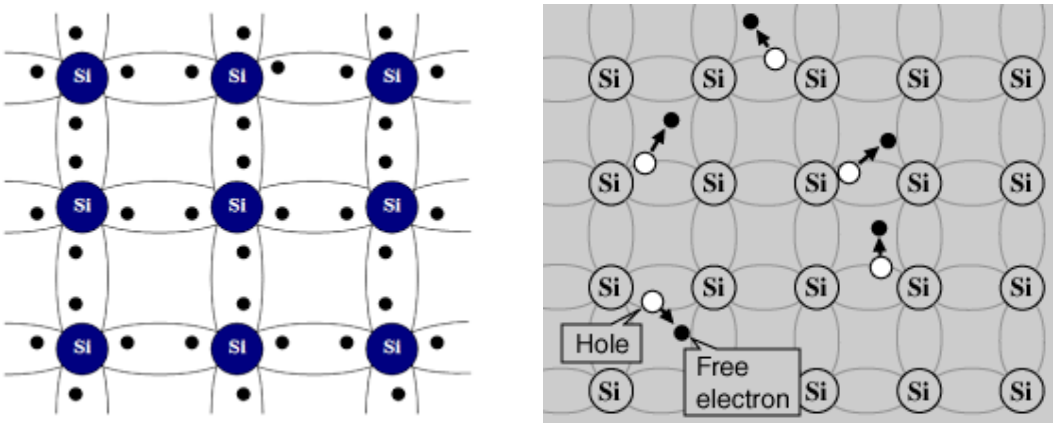
Types of semiconductors:

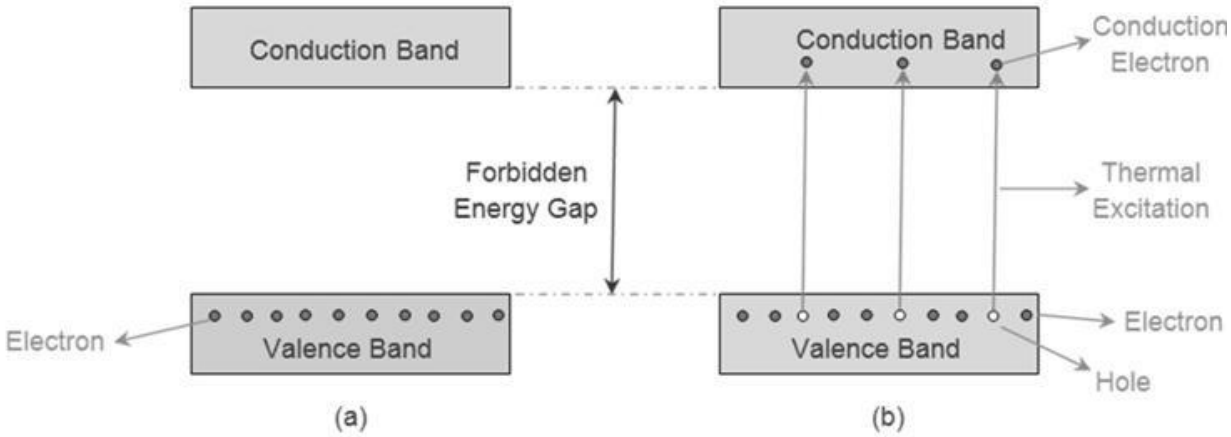
Depending on the semiconductor, it can be classified into two types.

1. Intrinsic Semiconductor.
2. Extrinsic Semiconductor.

Intrinsic Semiconductor:

The semiconductor which is pure and having the number of electrons in conduction band equal to number of holes in valance band is called as intrinsic semiconductor. The examples of intrinsic semiconductor are pure silicon and pure germanium crystals. At temperature T = 0K, the valence band of the Si is completely filled and all the states in the conduction bands are vacant as shown in Figure. When the temperature is increased, due to the thermal energy the covalent bond of Si breaks. Now, the electrons in the valance are transferred to the conduction band. At the same time, equal number of holes is present in the valance band. Therefore, the number of electrons that are moved to the conduction band is exactly equal to the number of holes in the valance band.





Extrinsic Semiconductors:

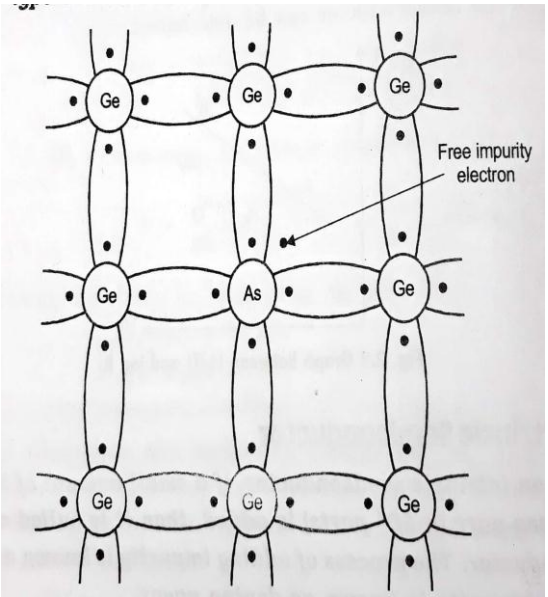
When small quantities of selected impurities are added to an intrinsic semiconductor it becomes an extrinsic semiconductor. Depending upon the type of impurity extrinsic semiconductors are of two types, namely

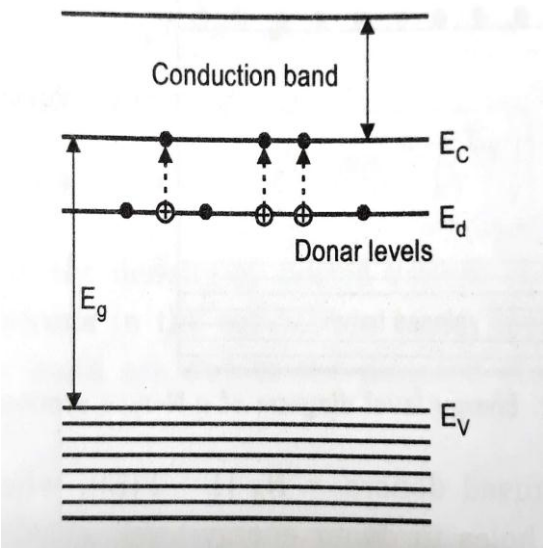
1. N – type semiconductor.
2. P – type semiconductor.

N – Type Semiconductors:

Generally, pure semiconductors have four valence electrons and can form four covalent bonds. When a pentavalent impurity, say Arsenic (As) which have five valence electrons is doped with pure Ge, the four valance electrons of As is making covalent bond with 4 electrons of Si atom and one electron is left out alone. This electron is present in the donor level which is lying just below the conduction band as shown in Figure. This energy level is called donor level and it is represented as E_d. Now the As atom is ready to 'donate' this single electron. When a

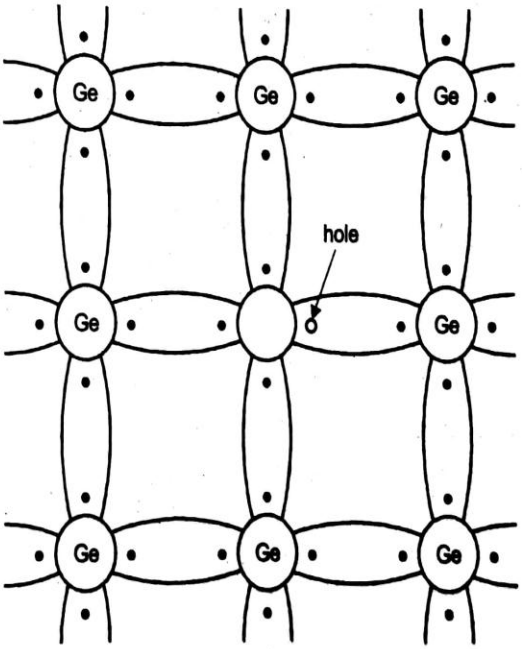
small amount of energy is supplied, As donates the electron to the conduction band and become into positive ion. In N - type semiconductor, holes are minority current carriers and electrons are majority current carriers. Such type of semiconductor is called 'N-type semiconductor' or 'DONOR'.

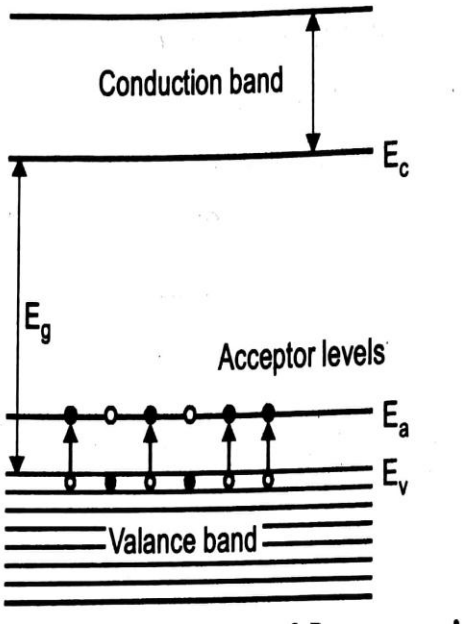




P– Type Semiconductors:

When a trivalent impurity say Boron (which have three valence electrons) is doped with pure Ge, the 3 valance electrons of Boron making covalent bond with 3 electrons of Ge and the 4^{th} electron of Ge does not have a pair, so a 'hole' exists in Boron atom. This means that Boron is ready to 'accept' an electron from Ge to fill the hole. This hole is present in the donor level of Boron atom which is lying just above the valance band as shown in Figure. This energy level is called as acceptor level and it is represented as E_a. When a small amount of energy is supplied, the electron in the valance band move to the acceptor and the Boron become into negative ion. In P - type semiconductor, holes are majority current carriers and electrons are minority current carriers. Such type of semiconductor is called 'P-type semiconductor' or 'ACCEPTOR'





Non-equilibrium properties of carriers

Excess electrons in the conduction band and excess holes in the valence band may exist in addition to the thermal-equilibrium concentrations if an external excitation is applied to the semiconductor.
The creation of excess electrons and holes means that the semiconductor is no longer in thermal equilibrium.

Carrier generation and recombination

Generation ⇒ process whereby electrons and holes are created

Recombination ⇒ process whereby electrons and holes are coincided and lost.

A sudden change in temperature or optical excitation can generate excess electrons and holes creating a nonequilibrium condition.

Non-equilibrium properties of carriers

Semiconductors in Nonequilibrium Conditions

Injection ⇒ A process of introducing excess carriers in semiconductors.

Generation and recombination are two types:

(i) Direct band-to-band generation and recombination and

(ii) the recombination through allowed energy states within the bandgap, referred to as traps or recombination centers.

Non-equilibrium properties of carriers

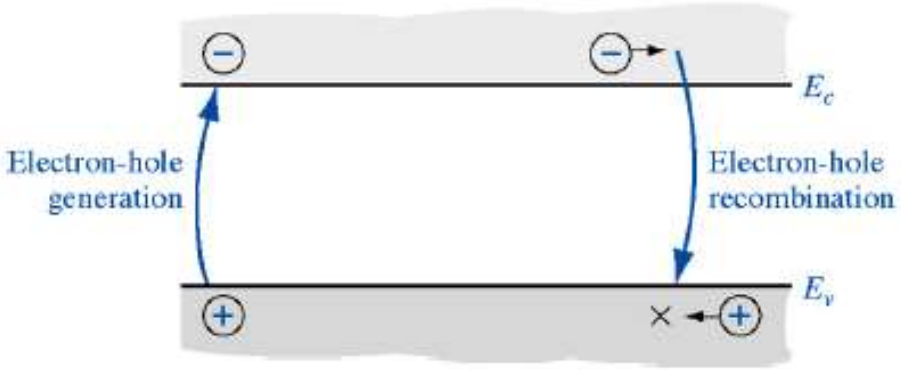
Direct band-to-band generation and recombination

Thermal equilibrium:

The random generation-recombination of electrons-holes occur continuously due to the thermal excitation.

In direct band-to-band generation-recombination, the electrons and holes are created-annihilated in pairs:

$$G_{n0} = G_{p0} \qquad R_{n0} = R_{p0}$$



At thermal equilibrium, the concentrations of electrons and holes are independent of time; therefore, the generation and recombination rates are equal, so we have,

$$G_{n0} = G_{p0} = R_{n0} = R_{p0}$$