

## MODULE - 1

# QUANTUM MECHANICS

⇒ Quantum Mechanics :-

It is a physical science dealing with the behaviour of matter and energy on the scale of atoms and sub-atomic particles of the waves.

⇒ Wave Particle Duality :-

1. Photon and electron both behave as particle and wave.
2. Wavelength of particle,  $\lambda = \frac{h}{p}$  (De Broglie's Equation).

where  $h$  = Planck's constant.

Electron	Tennis Ball
1. Charge = $1.6 \times 10^{-19} C$ .	
2. Mass, $m = 9.1 \times 10^{-31} kg$ .	Mass, $m = 0.058 kg$ .
3. Velocity, $v_1 = 1 \times 10^5 m/s$ (assumed)	Vel, $v_2 = 50 m/sec$ .
4. $p_1 = mv = 9.1 \times 10^{-26} kg m/s$	$p_2 = 2.9 kg m/sec$ .
5. $K.E = \frac{1}{2}mv^2 = \frac{p^2}{2m} = 28.4 meV$	$K.E = 72.55$

Electron.

6. Wavelength,  $\lambda_1 = 7.2 \text{ nm}$ .

Tennis Ball

$$\lambda_2 = 9.1 \times 10^{-32} \text{ m.}$$

→ By considering the properties of electron and tennis ball, we can say that,

$$\boxed{p_2 \gg p_1 \\ \lambda_2 \ll \lambda_1}$$

As by De Broglie's equation,

$$\boxed{\lambda \propto \frac{1}{p}}$$

\* Useful Relations :-

→  $k = \text{wave vector} = \text{wave number} = \text{Boltzmann's}$

→  $k = \frac{2\pi}{\lambda}$  coefficient.

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

$$\therefore p = \frac{h}{\lambda} = \left(\frac{h}{2\pi}\right) \left(\frac{2\pi}{\lambda}\right)$$

$$p = \hbar k$$

So

$$\boxed{p = \hbar k}$$

where,

$$\hbar = 1.05 \times 10^{-34} \text{ Js}$$

→ Energy of a photon,  $E = h\nu$

$$= \frac{hc}{\lambda}$$

$$\Rightarrow E = \left( \frac{h}{2\pi} \right) (2\pi\nu)$$

$$\Rightarrow [E = \hbar\nu]$$

$$\left. \begin{array}{l} \text{As, } \frac{c}{\lambda} = \nu \\ \text{and } 2\pi\nu = \omega \end{array} \right\}$$

→ So, by the given above relations, we can say that,

$$[p \propto k]$$

where,  $k$  = wave number.

and,

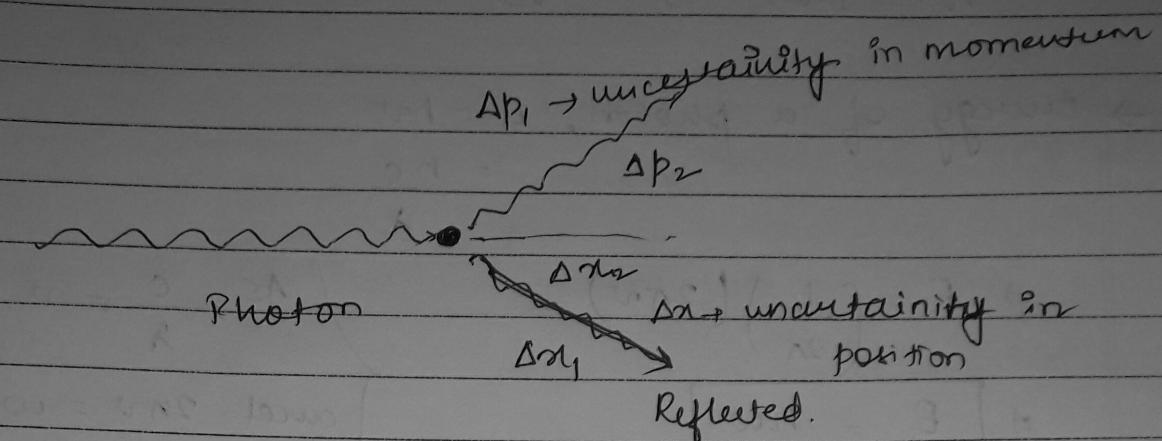
Also,

$$[E \propto \omega]$$

⇒ Heisenberg's Uncertainty Principle :-

→ It is impossible to calculate the exact position and momentum of any small ~~was~~ moving particles like electron, photon, in a simultaneous manner. In other words it is not possible to calculate exact change in position or change in momentum of

reflected photon/e<sup>-</sup> get struck by a photon/electron.



→ If  $\Delta x$  is error in determining position and  $\Delta p$  is error in determining momentum then Heisenberg's Uncertainty principle suggests that,

$$\Delta p \Delta x = \frac{h}{4\pi} = \frac{\hbar}{2} \quad \text{--- (1)}$$

$$p = mv$$

$$\Delta p = m\Delta v + \underbrace{v\Delta m}_{\text{zero}}$$

$$\Rightarrow \Delta p = m\Delta v \quad \text{--- (ii)}$$

Putting the value of (ii) in eqn (1)  
we get

$$m\Delta v \cdot \Delta x = \frac{h}{4\pi}$$

$$\therefore \boxed{\Delta v \cdot \Delta x = \frac{h}{4\pi m}} \quad \text{--- (iii)}$$

$\Rightarrow$  Energy :-

$$\Delta x \cdot \Delta p \geq \frac{h}{4\pi}$$

Multiplying and dividing we get,

$$\left( \frac{\Delta x \cdot \Delta p}{\Delta t} \right) \Delta t \geq \frac{h}{4\pi}$$

$$\left( \frac{\Delta x \cdot \Delta p}{\Delta t} \right) \Delta t \geq \frac{h}{4\pi}$$

$$\Rightarrow \left( \frac{\Delta x \cdot F \Delta t}{\Delta t} \right) \Delta t \geq \frac{h}{4\pi}$$

$$\Rightarrow (F \Delta x) \Delta t \geq \frac{h}{4\pi}$$

$$\Rightarrow \Delta E \cdot \Delta t \geq \frac{h}{4\pi}$$

- (IV)

As  
By Newton's second  
law,  
 $F = ma$

$$F = \frac{dp}{dt}$$

$$p = mv$$

$$\frac{dp}{dt} = m \cdot \frac{dv}{dt} = ma$$

$\Rightarrow$  So uncertainty in energy is also applicable through Heisenberg's uncertainty principle.

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

$$K.E = \frac{1}{2m} p^2$$

$$p = \sqrt{2m(K.E)}$$

$$\lambda = \frac{h}{\sqrt{2m(K.E)}}$$

$$K.E = \frac{1}{2} mv^2 = qV$$

Now

$$q = e.$$

$$\lambda = \sqrt{\frac{150}{v}} \text{ Å}$$



Q

An electron is confined to region of width  $5 \times 10^{-11} \text{ m}$ , which is its uncertainty in posn,  $\Delta x$ . Estimate the minimum uncertainty in its momentum. Also calculate uncertainty in its velocity.

$$\Delta x \cdot \Delta p \geq \frac{h}{4\pi} = \frac{\hbar}{2}$$

Given :-

$$\Delta x = 5 \times 10^{-11} \text{ m.}$$

$$\hbar = 1.05 \times 10^{-34}$$

Then,

$$\Delta p \cdot 5 \times 10^{-11} \geq \frac{1.05 \times 10^{-34}}{2 \times 1}$$

$$\therefore \Delta p \geq \frac{1.05 \times 10^{-34}}{10 \times 10^{-11}}$$

$$\therefore \Delta p \geq \frac{1.05 \times 10^{-34}}{10^{-10}}$$

$$\therefore \Delta p \geq 1.05 \times 10^{-24} \text{ kg m/s.}$$

$$\Delta n \cdot \Delta V = \frac{h}{4\pi m}$$

$$\Rightarrow \Delta V = \frac{h}{2\pi m \cdot \Delta n}$$

$$\Rightarrow \Delta V = \frac{1.05 \times 10^{-34}}{2 \times 9.1 \times 10^{-31} \times 10^{-34} \times 5}$$

$$= \frac{1.05 \times 10^{-34}}{10 \times 9.1 \times 10^{-42}}$$

$$= \frac{0.11 \times 10^{-34}}{10^{-41}}$$

$$= 0.11 \times 10^7 \text{ m/e. Ans}$$

→ ~~The wave function~~

→ Schrodinger equation :-

→ The wave function  $\psi$  contains information on all measurable parameters of the particle.

→  $\psi \psi^*$  is the probability density of finding particles between  $x$  and  $x+dx$ .

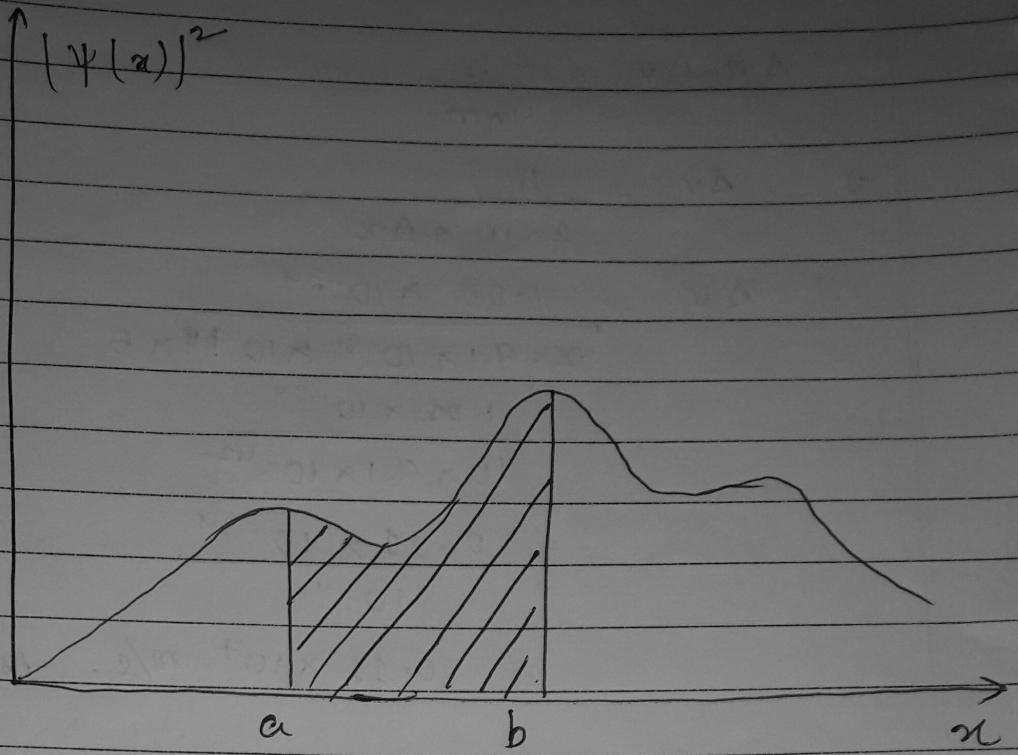
If  $\psi(x, t)$  be real, probability of finding the particle between  $x$  and  $x+dx$ , will be

$$|\psi(x, t)|^2 \cdot dx$$

→ Probability of finding particle between  $a$  &  $b$  is

$$\left[ \int_{x=a}^{x=b} |\psi|^2 \cdot dx \right]$$

a and



⇒ Some useful operators :-

1) Momentum operator :-

$$P_x = \frac{\hbar}{i} \frac{\partial}{\partial x}$$

$$\left. \begin{aligned} i^2 &= -1 \\ i &= \sqrt{-1} \end{aligned} \right\}$$

thus,  $\frac{\hbar}{i} \frac{\partial \psi}{\partial x} = P_x \psi$

2) Energy operator :-

$$\bar{E} = -\frac{\hbar}{i} \frac{\partial}{\partial t}$$

thus,  $\frac{\hbar}{i} \frac{\partial \psi}{\partial t} = E \psi$

3) Kinetic energy :-

$$KE = \frac{p_i^2}{2m} = \frac{1}{2m} \frac{\hbar}{i} \frac{\partial}{\partial x} \left( \frac{\hbar}{i} \frac{\partial \psi}{\partial x} \right)$$

$$\Rightarrow KE = -\frac{\hbar^2}{2m} \cdot \frac{\partial^2 \psi}{\partial x^2}$$

⇒ Properties of wave functions:-

1. It contains information on all measurable parameters of the particle.
2.  $\psi$  must be a solution of Schrodinger's equation.
3.  $\psi$  must be continuous also  $\frac{\partial \psi}{\partial x}$  must be continuous.  $\frac{\partial \psi}{\partial x}$  should
4.  $\psi$  must be normalizable.

$$\int_{-\infty}^{\infty} |\psi|^2 dx = 1.$$

⇒ Particle's wave function  $\psi(x, t)$  is given by.

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

$$i = \sqrt{-1}$$

$$\hbar = h = 1.05 \times 10^{-34} \text{ Js.}$$

→ Time independent Schrodinger equations :-

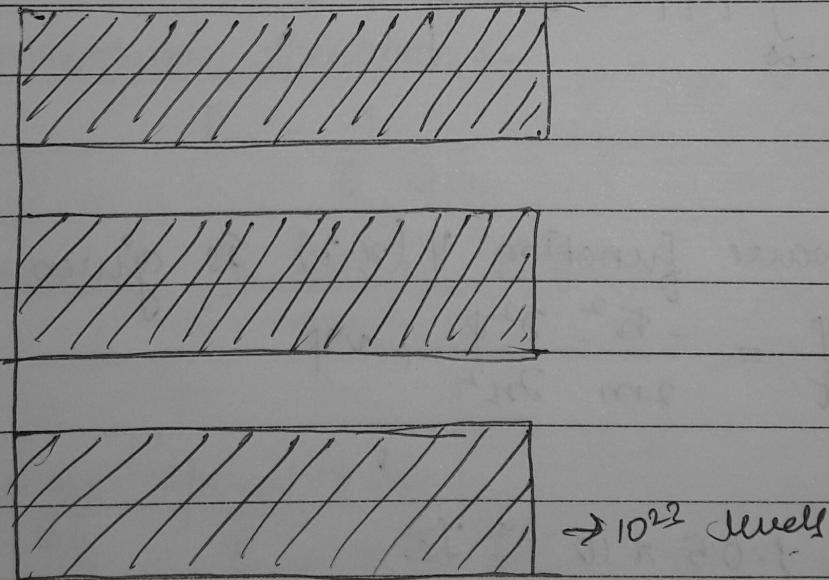
$$\left[ -\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} + V\psi \right] = E\psi$$

Kinetic energy                  Potential energy                  Total energy

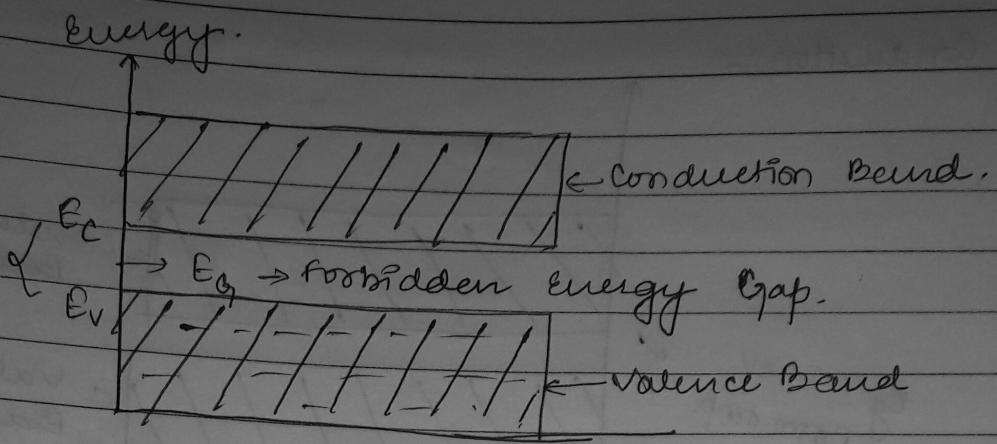
### \* Bonding Forces and Energy Band in Solid :-

→ Bonding Forces :-

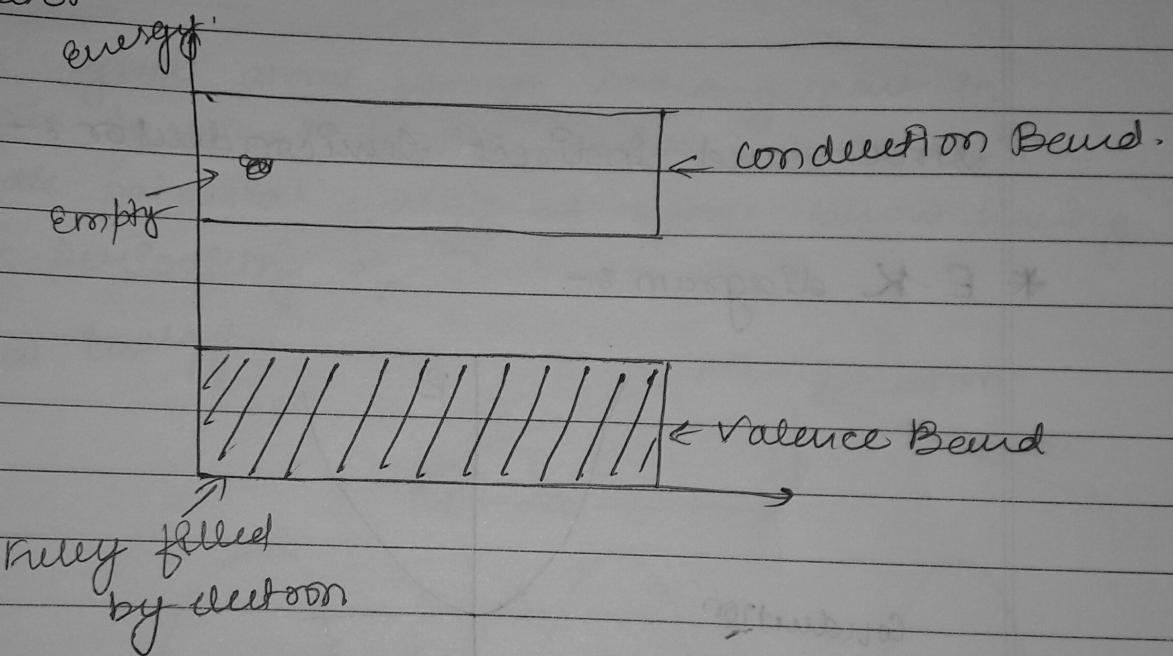
1. Ionic → transfer of electrons.
2. Covalent → sharing of electron.
3. Mixed Bonding →



Crystal

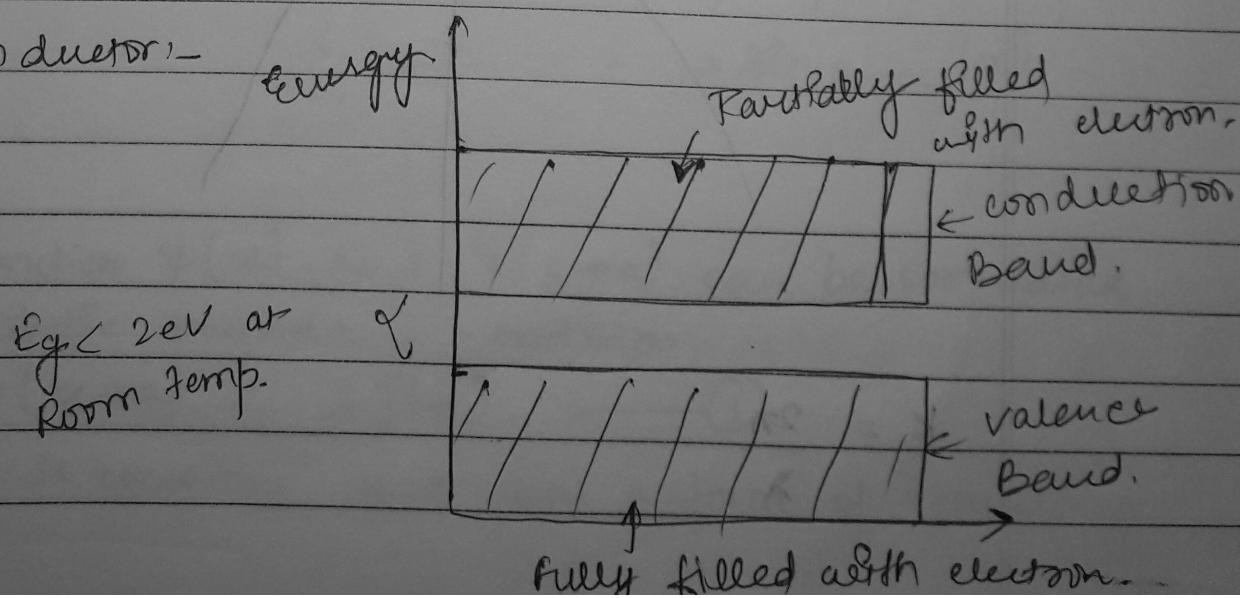


⇒ Insulator



~~eg~~  $E_g > 5 \text{ eV}$  at Room Temp. 300 K.

⇒ Semiconductor:-

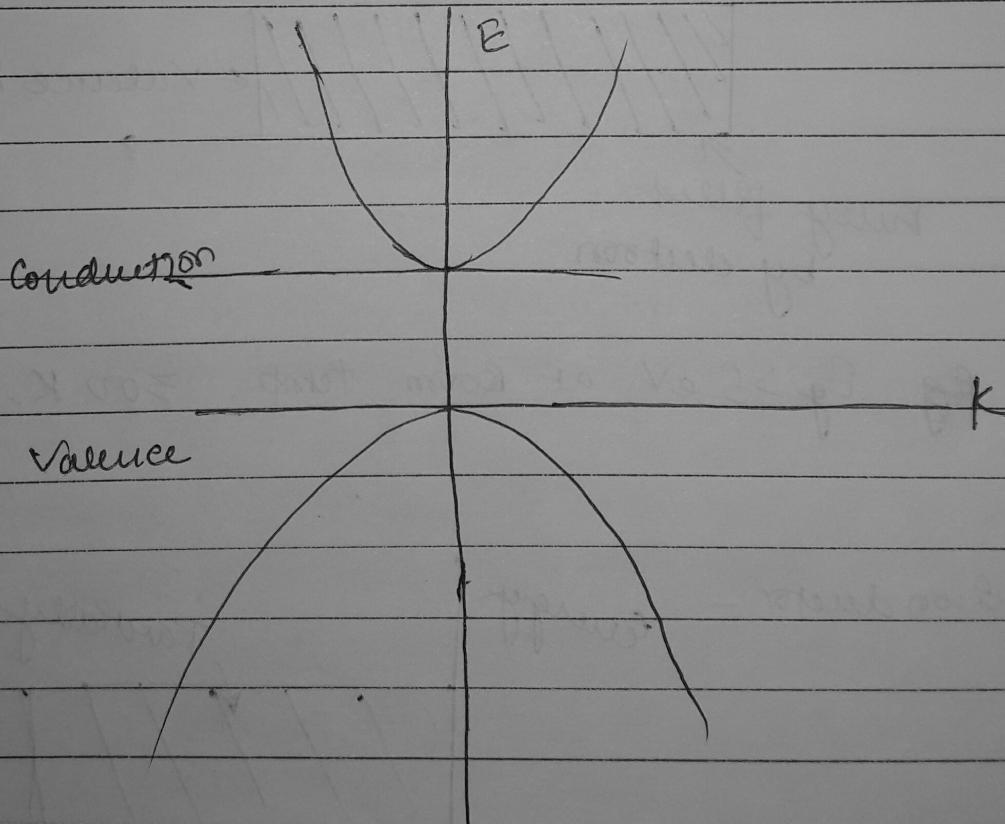


⇒ Conduction :-



⇒ Direct and Indirect Semiconductor :-

\* E-K diagram :-



$$k = \frac{2\pi}{\lambda}$$

$$\lambda = n$$

p

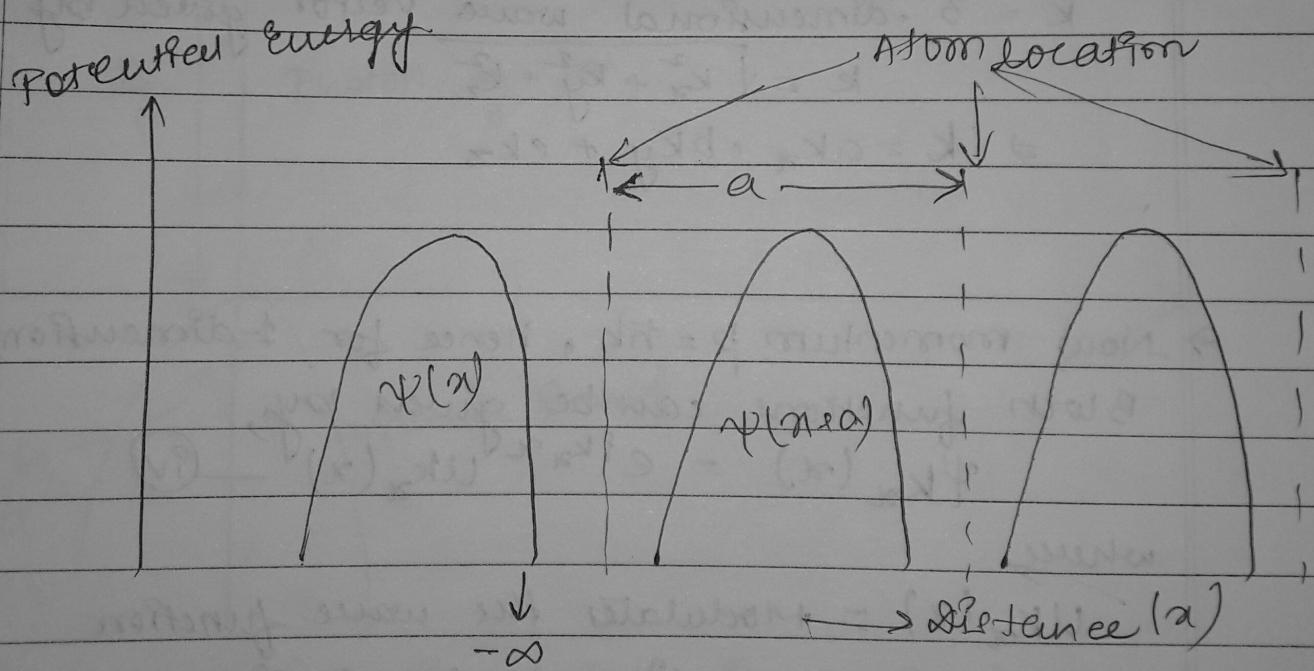
$$\Rightarrow p = n$$

$\lambda$

$$\Rightarrow p = \hbar k$$

→ KE is present in the indirect semiconductor.

→ In a crystal atoms common arrangement in periodic fashion is possible which gives rise to a periodic potential energy as shown below having lattice periodicity of  $a$ .



⇒ wave function  $\psi(x)$  and  $\psi(x+a)$  can be correlated by periodic boundary condition.

$$\psi(x+a) = \lambda \psi(x) \quad \text{--- (1)}$$

where  $\lambda$  be constant and has a form of travelling

wave along  $x$ -dim and can be expressed by

$$\lambda = e^{ikx} \quad \text{--- (II)}$$

where

$k$  = wave number or propagation constant

in  $x$ -dim given by  $\frac{2\pi}{\lambda}$ .

→ For such periodic functions, Bloch generalized the expression of electron wave fun as

$$\psi_k(x) = e^{ikx} u_k(x) \quad \text{--- (III)}$$

where,

$x$  = 3-D position vector

and  $u_k(x)$  = modulating function representative of lattice periodicity in 3-dimensions.

$k$  = 3-dimensional wave vector given by

$$k = \sqrt{k_x^2 + k_y^2 + k_z^2}$$

$$\Rightarrow k = a k_a + b k_y + c k_z$$

→ Now momentum  $p = \hbar k$ , hence for 1-dimension,

Bloch functions can be given by,

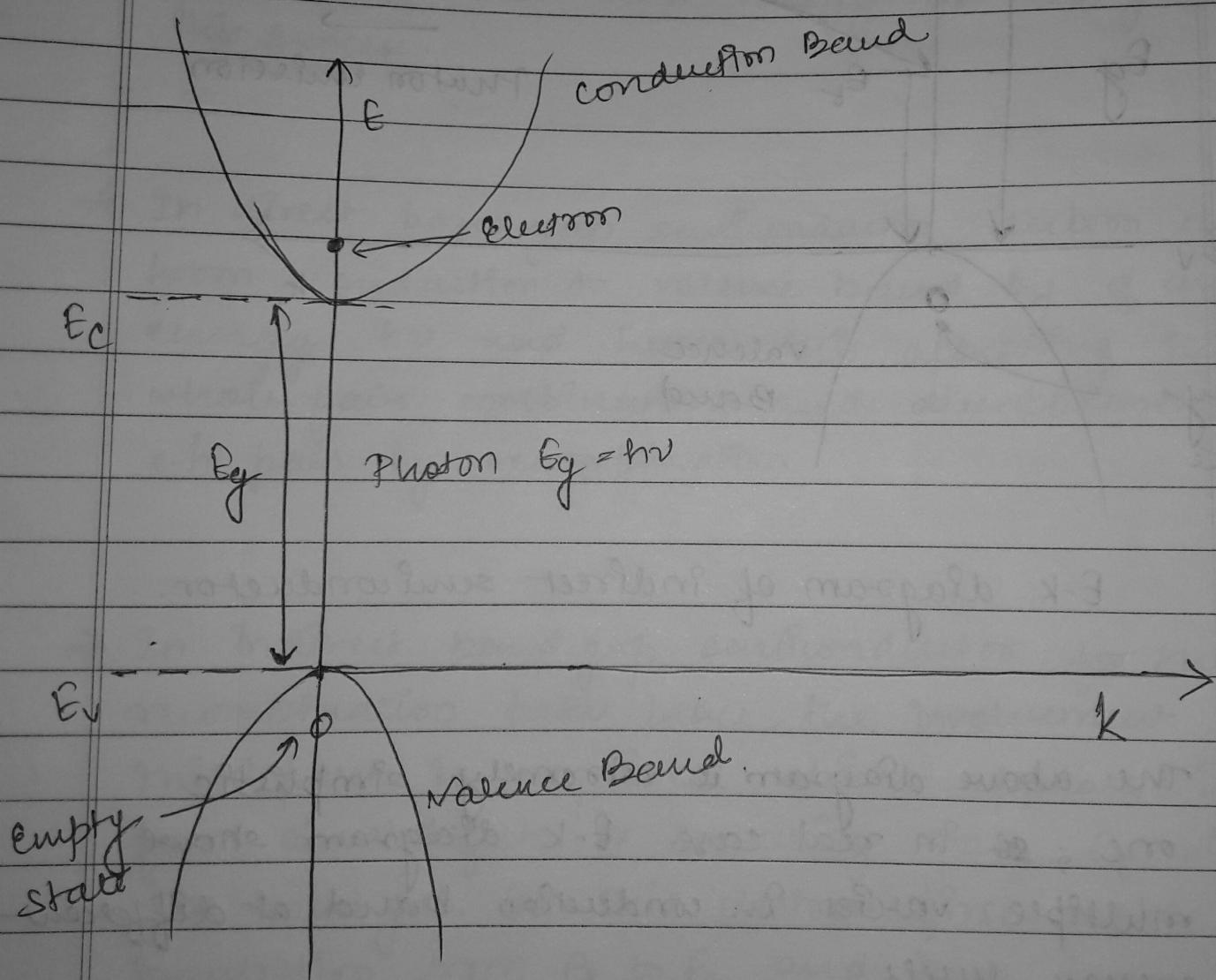
$$\psi_{k_a}(x) = e^{ik_a x} u_{k_a}(x) \quad \text{--- (IV)}$$

where,

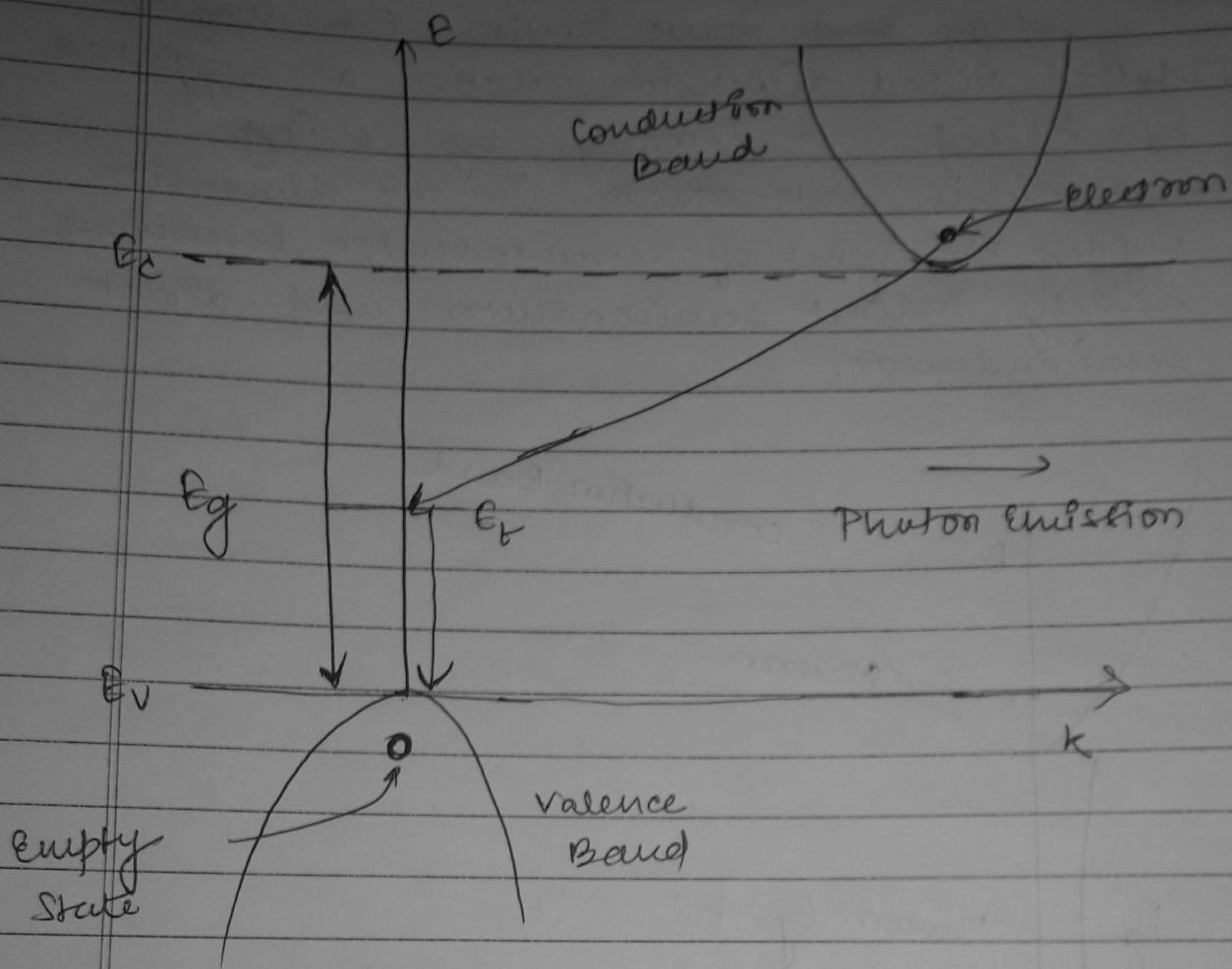
$u_{k_a}(x)$  = Modulates the wave function

according to the lattice in 1-dimension  
along  $x$ -dim

→ The energy and wave function E-K diagram were plotted called dispersion relation as suggested by Kronig and Penney, by solving Schrödinger wave equation in one dimension suggest two types of semiconductor behaviours namely indirect semiconductor and direct semiconductor.



E-K diagram of Direct Semiconductor.

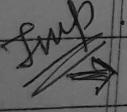


E-k diagram of indirect semiconductor.

- ⇒ The above diagram is extremely simplistic one, ~~so~~ in real case E-k diagram shows multiple valleys in conduction band at different energy levels.
- ⇒ In direct band-gap semiconduction the min<sub>m</sub> of conduction band and max<sub>m</sub> of valence band that is  $E_c$  and  $E_v$  occurs at same value of  $k$  at 0 which justify that carrier have

zero momentums, hence only potential energy is present.

- In indirect band-gap semiconductor,  $E_c$  and  $E_v$  are at different values of  $k$  justifying that momentum is not zero, and hence conduction band has both potential as well as kinetic energy. Hence momentum and energy got changed in NC process.
- In direct band-gap semiconductor electron can fall from conduction to valence band by emitting energy  $h\nu$  and hence this appearing the whole-pair combination, and disappearing e-h pair by recombination.
- In indirect band-gap semiconductors for the recombination takes place, the movement of hole pair is required which appears in the form of a defect or impurity state,  $E_f$  within the band-gap. In this electron first make transition from  $E_c$  to  $E_f$  and then from  $E_f$  to  $E_v$  to complete recombination process.

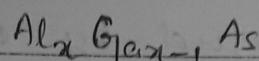
 It can be clearly concluded that rate of recombination in direct band-gap semiconductor is several order of magnitude higher than that observed in indirect band-gap semiconductor.

→ For opto electronic direct band gap using GaAs is preferred in place of Si and As is uses indirect band-gap semiconductor process.

### # Variation of energy band with Alloy composition:-

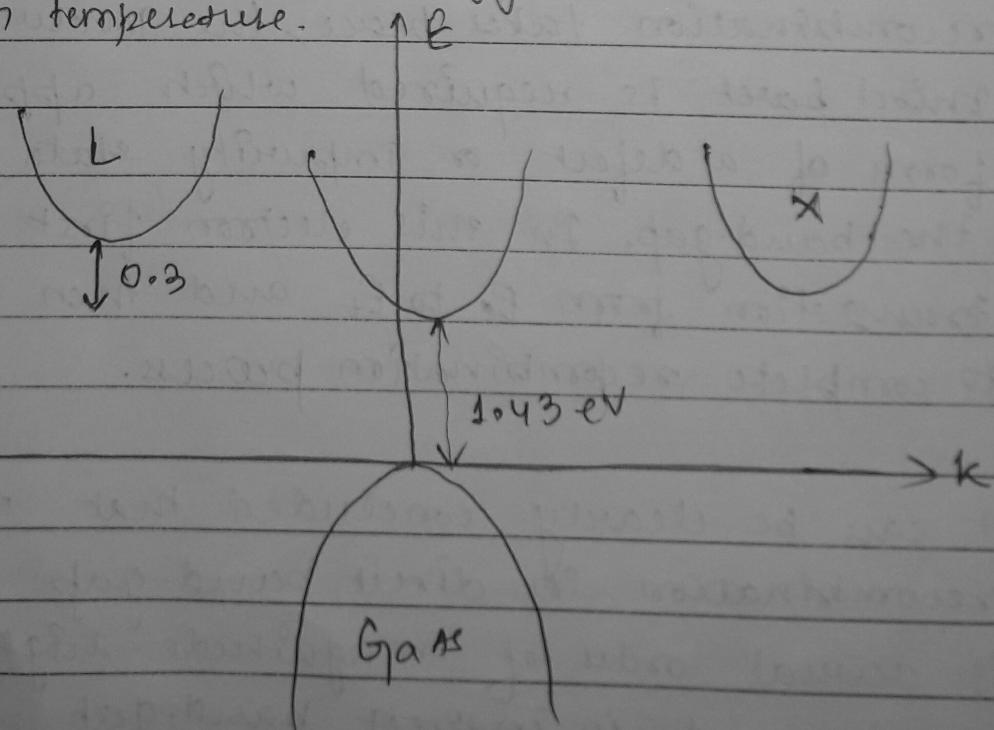
→ Band structure of alloy changes in accordance of composition changes.

Example:-



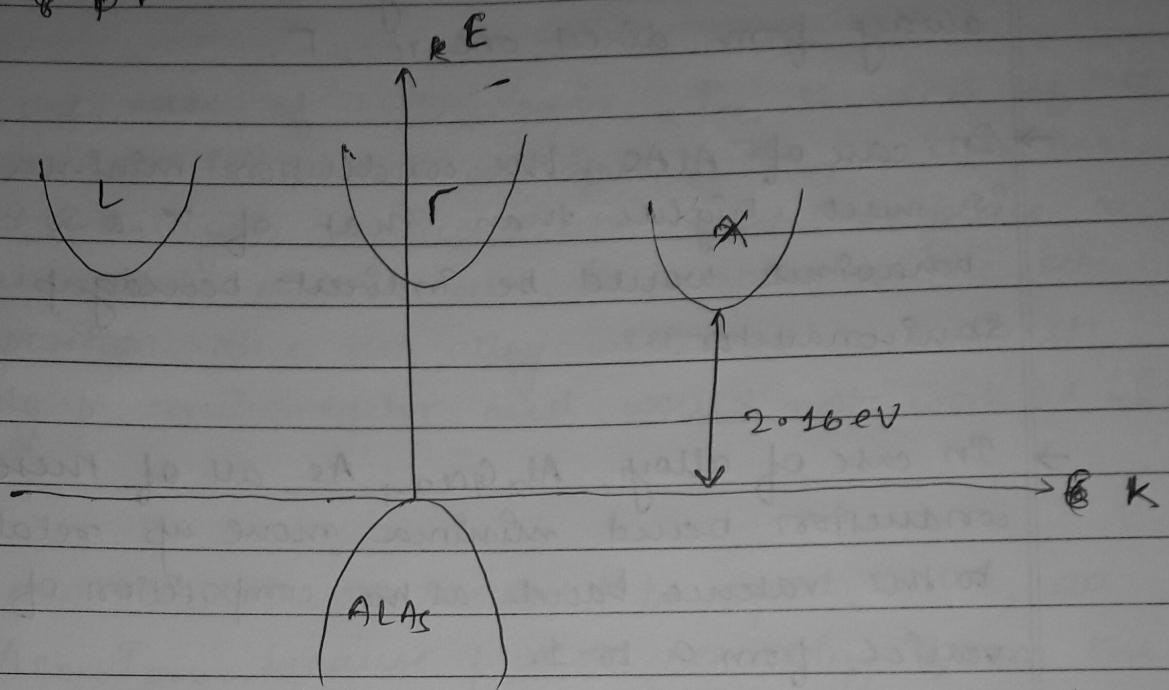
→ Consider a quaternary alloy  $Al_x Ga_{1-x} As$ . In this the energy band changes with respect to the value of  $x$  (composition of element).

→ Consider GaAs which is a direct bandgap semiconductor, with energy band of 1.43 eV at room temperature.

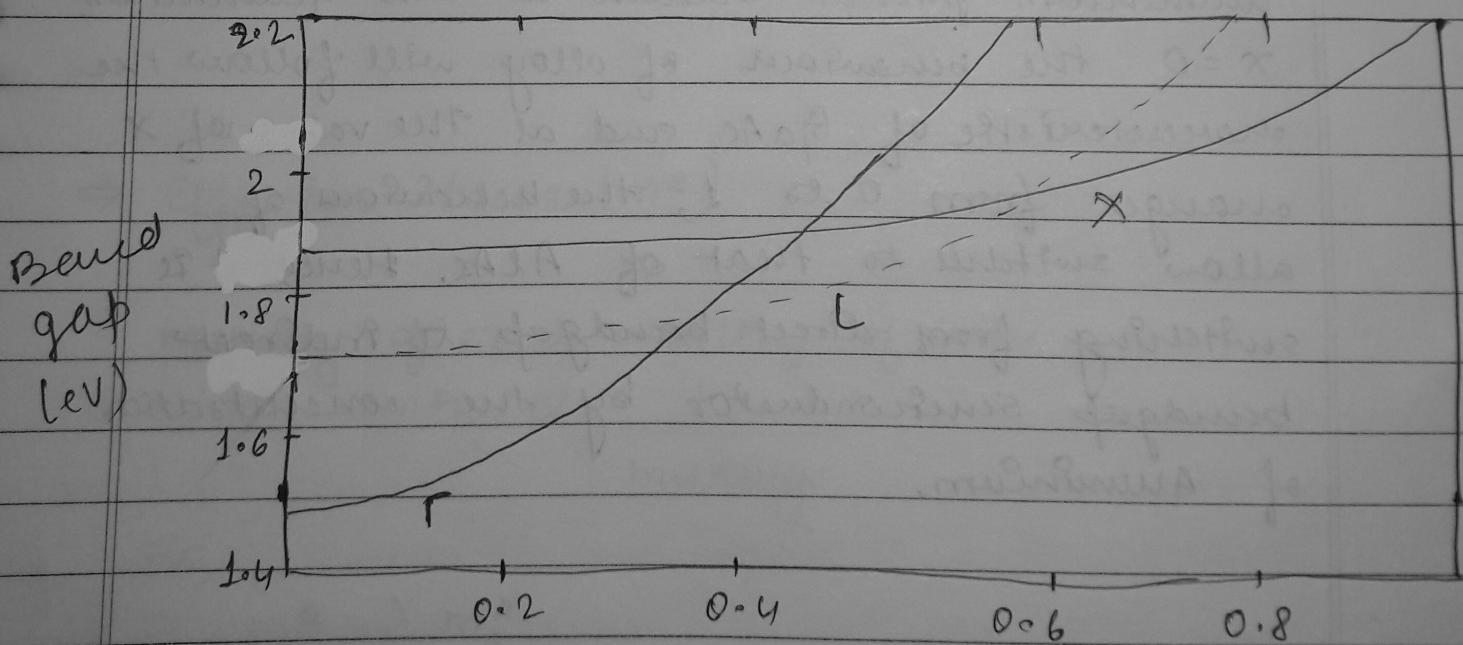


E-k diagram of GaAs

for the direct bandgap semiconductor, consider  
 $k=0$  for which conduction band is minimum  
at  $\vec{k} = \vec{0}$ .



E-k diagram of AlAs.



Aluminum fraction ( $x$ )

Position of three conduction band minima for

Al<sub>x</sub>Ga<sub>1-x</sub>As

- In case of GaAs, direct bandgap semiconductor phenomenon is present due to the fact that two indirect bands say  $\Gamma$  and L are far away from direct one, i.e., X.
- In case of AlAs, the conduction minima  $\Gamma$  is much higher than that of X. So, its behaviour would be indirect bandgap semiconductor.
- In case of alloy,  $Al_xGa_{1-x}As$  all of these conduction band minima move up relative to the valence band as the composition of X varies from 0 to 1.  
In other words we can say that the behaviour of alloy is governed by the concentration of aluminium present because at low Aluminium  $x=0$ , the behaviour of alloy will follow the characteristic of GaAs and as the value of X changes from 0 to 1, the behaviour of alloy switches to that of AlAs. Hence it is switching from direct bandgap to indirect bandgap semiconductor by the concentration of Aluminium.
- The compositions having higher value of 38% of Al the indirect conduction band comes to play and the alloy switches to indirect bandgap to direct bandgap semiconductor.

Hence higher Aluminium mole fraction tends the alloy from direct semiconductor to indirect one.

- In the case of LED,  $\text{GaAs}_{1-x}\text{P}_x$  is used if the composition is set up as  $\text{GaAs}_{0.55}\text{P}_{0.45}$ , then the direct bandgap semiconductor will take place and light will be emitted out. But above to the set composition value the alloy will work as indirect bandgap semiconductor and would not work at LED.
- For the red LED,  $x$  should be equal to 0.4, so  $\text{GaAs}_{0.6}\text{P}_{0.4}$  because photon resulting from the direct transition from the band to valence band ~~using~~ is in red position of spectrum about 1.9 eV.
- ⇒ Effective Mass  $- (m^*)$
- mobility of  $e^- >$  mobility of holes.  
 $m \rightarrow m^* \propto \frac{1}{\text{mobility}}$

So,

$$m_h^* \rightarrow m_e^*$$

- When an electron is in a periodic potential under (crystal/lattice combination) accelerated by an electric or magnetic field, then the mass of electron varies with velocity. In other words, the mass of electron is a function of velocity and is termed as effective mass of electron  $m^*$ .
- Electron moves in a free space differently with respect to its movement in periodic potential considering distance travelled is greater than the lattice space, then electrodynamic equations can be applied by considering effective mass. In doing so most
- In doing so most of the influences arises by lattice got balanced and electron and holes are treated as to be almost free carriers in most of condition.
- For electron in a solid the effective mass is usually stated as rest mass of electron. In other words it is a quantity that is used to simplify band structure by constructing an analogy to the behaviour of a free particle within that mass.

→ Effective mass of hole is greater than mass of electrons because mobility of holes are less than mass of electrons. Also in E-k diagram top of the valence band is flatter than that of lower of conduction band. Hence, hole concentration is higher resulting higher effective mass.

The effective mass is given by,

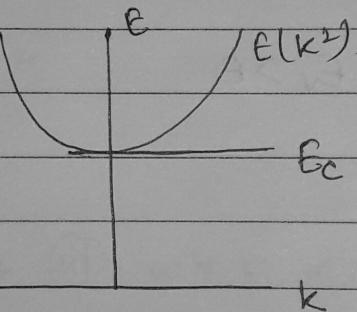
$$m^* = \frac{\hbar^2}{(\partial^2 E / \partial k^2)}$$

Ques:

Effective mass in structure of Band:-

→ For conduction

Band:-



$$E - E_c = ck^2$$

Differentiating with respect to k

we get

$$\frac{dE}{dk} = 2ck$$

$$\frac{d^2E}{dk^2} = 2c > 0 \quad (\text{As } E > E_c)$$

$$\text{So, } \frac{d^2E}{dk^2} > 0$$

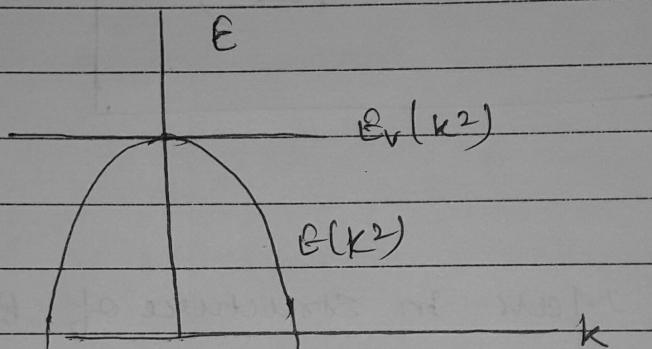
Now,

$$\frac{1}{\hbar^2} \frac{d^2 E}{dk^2} = \frac{1}{m_n^*}$$

$$\Rightarrow \frac{1}{\hbar^2} (2c_1) = \frac{1}{m_n^*}$$

$m_n^* > 0$ ,  $e^-$  as heavy particle.

→ For valence band:-



$$E_v - E = ck^2, E_v > E$$

$$-\frac{dE}{dk} = 2c_1 k$$

$$-\frac{d^2 E}{dk^2} = 2c_2$$

$$\Rightarrow \frac{d^2 E}{dk^2} = -2c_2 < 0$$

So

Now,

$$\frac{1}{\hbar^2} \frac{d^2 E}{dk^2} = \frac{1}{m_n^*}$$

$$\Rightarrow \frac{1}{\hbar^2} (-2c_2) = \frac{-1}{m_n^*}$$

so

$$m_n^* < -ve, e^- \text{ as light particle.}$$

~~Imp.~~

Q. Prove that effective mass  $m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)}$ .

→ As we know,

$$p = \hbar k \quad \text{--- (1)}$$

Also,

$$K.E. = \frac{1}{2}mv^2 = \frac{(mv^2)}{2m} = \frac{p^2}{2m} \quad \text{--- (2)}$$

So,

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

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

$$E = mc^2$$

$$E = h\nu = \frac{hc}{\lambda}$$

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

$$\hbar = \frac{h}{2\pi} \text{ and } k = \frac{2\pi}{\lambda}$$

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

∴ ~~p = h/k~~

$$\therefore p = \hbar k$$

Now,

Differentiating (ii) w.r.t  $k$ ,

we get

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

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

Again,

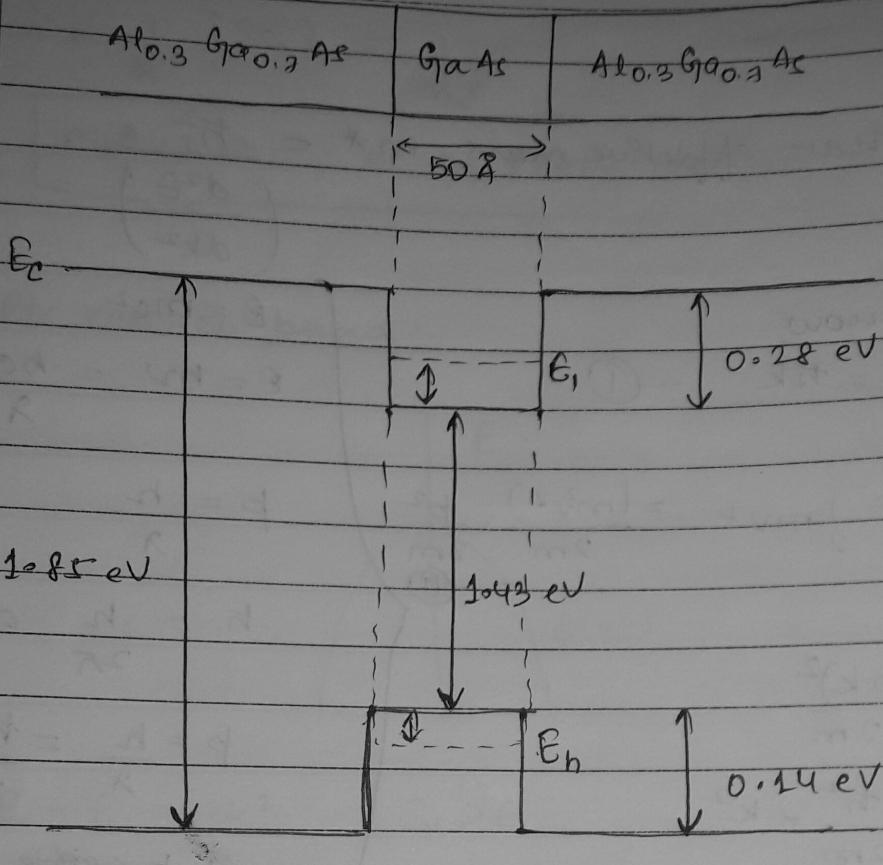
$$\frac{d^2E}{dk^2} = \frac{\hbar^2}{m}$$

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

For the case of crystal, we can interchange  $m$  by  $m^*$   
i.e.,  $m = m^*$  (For crystal)

, proved.

→ Quantum Well :-



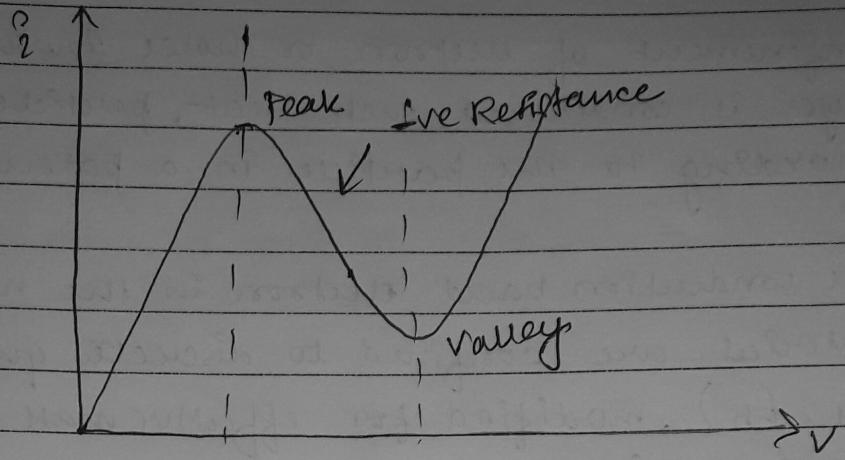
$$E_g = (1.043 + E_i + E_h) \text{ eV}$$

- By using quantum mechanical confinement, energy level can be altered.
- By using quantum well concept energy of alloys / composites can be enhanced than that of their usual values.
- Then layer of  $\text{GaAs}$  is sandwiched between two layers of  $\text{AlGaAs}$  which has a wider

bandgap man GaAs.

- Confinement of electron or hole towards a very thin layer is considered such that, particle behave according to the particle in a potential well.
- The conduction band electron in the narrow gap material are confined to discrete quantum states ( $E_1, E_h$ ), modified for effective mass and finite barrier height.
- The formation of discrete quantum state in GaAs here changes the energy at which photon can be emitted.
- An electron at discrete conduction band  $E_1$  of GaAs quantum well ~~leaving~~ giving off a total photon of energy ( $E_1 + E_g + E_h$ ) to shift ~~the~~ <sup>in</sup> valence band holes. The net bandgap energy is now greater than that of conventional one.
- This concept is used in LCD, LASER modulator efficiency enhancer, etc.

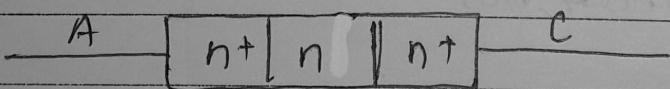
⇒ Gunn Diode:- (Transferred Electron Diode) :-



→ Microwave devices that work on the technique of transferred electron mechanism are called as Gunn diode. It was introduced by J.P. Gunn in 1962. In the Gunn Diode negative resistance character is taken place which make them applicable for microwave devices, oscillator and radar.



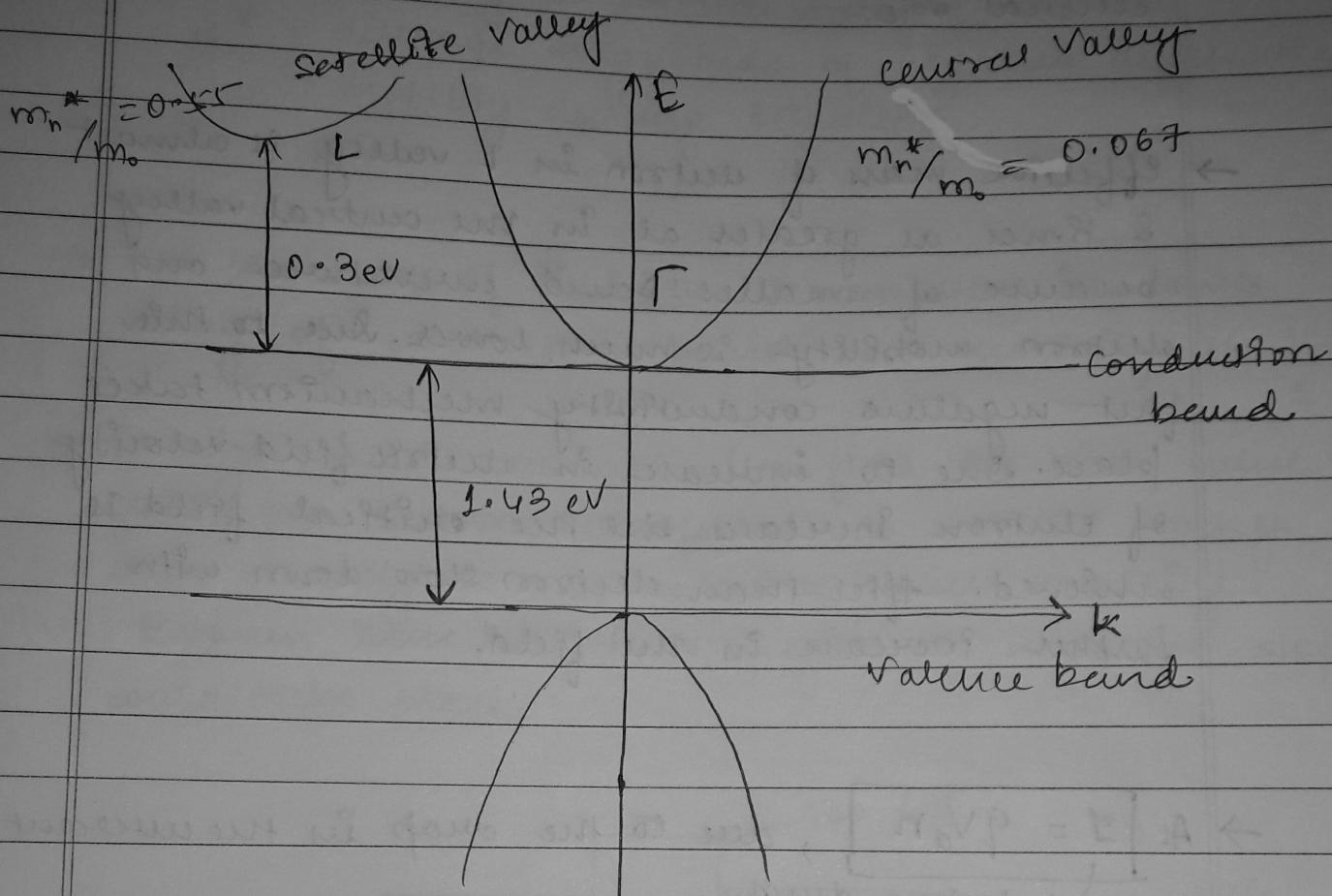
symbol of Gunn Diode



→  $3000 \text{ V/cm}$  is the high electric field.

⇒ In transferred electron mechanism, the conduction electrons of some semiconductor are shifted from a state of high mobility to a state of

low mobility by influence of high electric field.  
Negative conductance operation can be achieved  
in a diode.



Simplified band diagram of GaAs illustrating upper and lower valley in conduction band.

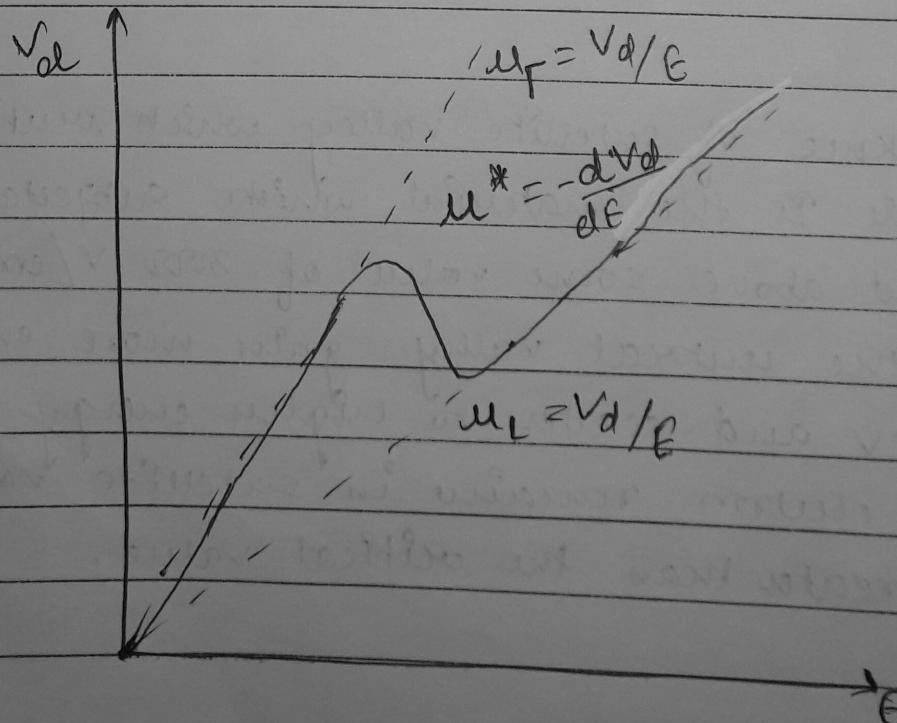
→ Presence of satellite valley which results in Gunn diode. If the material which subjected to electric field above some value of  $3000 \text{ V/cm}$ , the electron in the central valley gains more energy than  $0.3 \text{ eV}$  and scatter to higher energy valley at  $L$ . The electron remains in satellite valley till field is greater than the critical value.

→ Combined effective density of states for the upper valley is much greater than that of central one.

→ Effective mass of electron in L valley is almost 8 times as greater as in the central valley because of smaller band curvature and electron mobility is much lower. Due to this fact negative conductivity mechanism takes place. Due to increase in electric field velocity of electron increases till the critical field is achieved. After that electron slow down with further increase in the field.

→ At  $I = qV_d n$ , due to the drop in the current electron density.

In this region, having increase in field, a negative differential conductivity,  $dI/dE$  takes place.



Here,

$m_f$  = mobility in central valley,

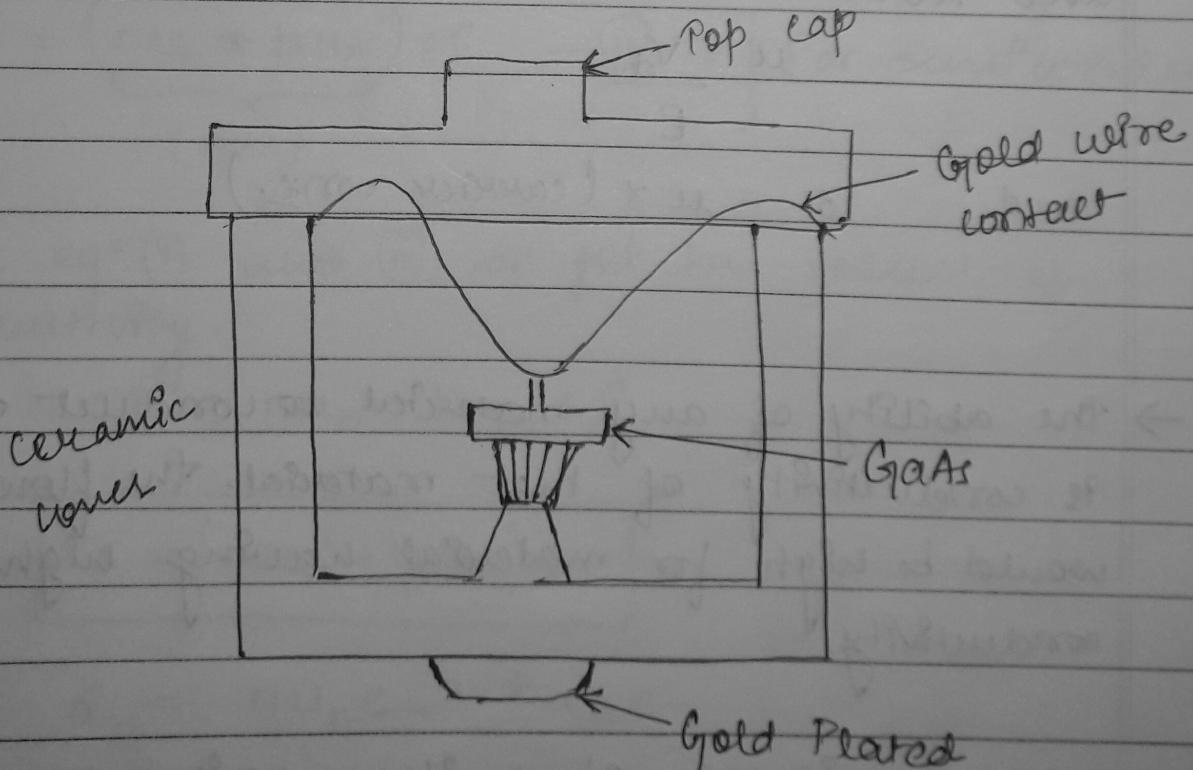
$m_s$  = mobility in satellite valley and

$m^*$  = average magnitude of negative differential mobility during transition.

→ For low value of field, the electron stay in lower valley of conduction band and mobility is  $\frac{V_d}{E}$

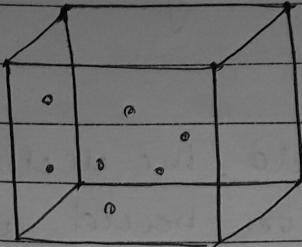
is high and constant with field. For high value of field, the electron transferred to satellite valley where velocity is smaller with lower mobility.

Between these two states region of negative slope could take place.



→ Mobility ( $\mu$ ) and conductivity ( $\sigma$ ) :-

$$\mu = \frac{V_d}{E}$$



→ (scattering phenomenon of  $e^-$ )

→ In an influence of electric field, phenomenon of  $e^-$  to move in a crystal is known to be mobility. Whereas conductivity is the product of mobility and carrier concentration.

$$\mu = \frac{V_d}{E}$$

and,  $\sigma = \mu \times (\text{carrier conc.})$

→ The ability of any material to conduct electricity is conductivity of that material. The flow of  $e^-$  would be high for material having high conductivity.

→ Mobility is value of drift velocity per unit of electric field strength. Hence, the faster the particle moves at a given electric field strength the larger the mobility.

$$\Rightarrow i = neAv_d$$

where,

$n$  = no. of electrons

$A$  = Area

$v_d$  = drift velocity.

$$\Rightarrow J = \frac{i}{A} = \frac{neAv_d}{A} = nev_d$$

$$\Rightarrow J = neuE$$

where,

$u$  = mobility

and  $E$  = electric field.

Also

$$J = \frac{\sigma E}{\rho} \quad \text{--- (Ohm's law)}$$

(Conductivity)

$$J = \underbrace{(n_e + p_p)}_{(n_u)} eE \quad \text{--- (II) } ] \text{ for semiconductors}$$

→ By eqn (I) and (II), we get the values of conductivity.

$$\sigma E = (n_e + p_p) e \rho^2$$

$$\Rightarrow \boxed{\sigma = (n_e + p_p) e}$$

$$\Rightarrow \sigma = n_e n_e + p_p p_p$$

↓  
current  
density due  
to electrons

for conductors

Q The mobility of free electrons and holes in a pure Ge are  $0.38$  and  $0.18 \text{ m}^2/\text{V}\cdot\text{s}$ , find the value of intrinsic conductivity assume  $n_i = 2.5 \times 10^{19} \text{ m}^{-3}$  at RT.

$\rightarrow$  As,  $n = p = n_i$  (At RT for intrinsic sc)  
So,

$$n_p = n_i^2$$

Given :-

$$u_n = 0.38 \text{ m}^2/\text{V}\cdot\text{s}$$

$$u_p = 0.18 \text{ m}^2/\text{V}\cdot\text{s}$$

So,

$$\begin{aligned} \sigma &= (u_n + u_p) n_i e \\ &= 0.56 \times 2.5 \times 10^{19} \times 1.6 \times 10^{-19} \\ &= 2.24 \times 10^0 \\ &= 2.24 (\text{cm})^{-1} \text{ Ans.} \end{aligned}$$

Q In a  $\alpha$ -Ge sample a donor-type impurity is added to the extent of 1 atom per  $10^8$  Ge. Find out the overall resistivity of the sample.

$\rightarrow$  we know that

$$\rho = \frac{1}{\sigma}$$

Given :-

$$u_n = 3800 \text{ cm}^2/\text{V}\cdot\text{s}$$

$$u_p = 1800 \text{ cm}^2/\text{V}\cdot\text{s}$$

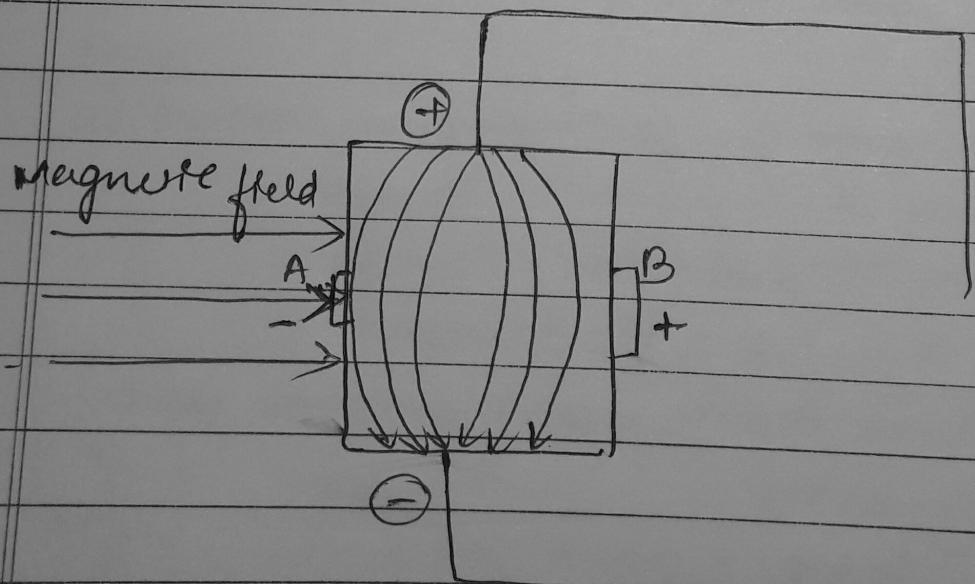
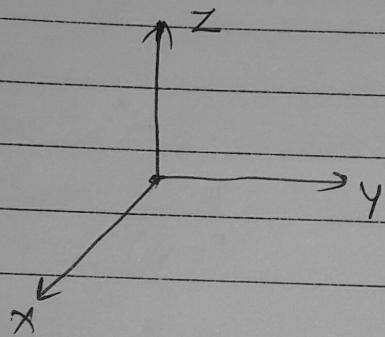
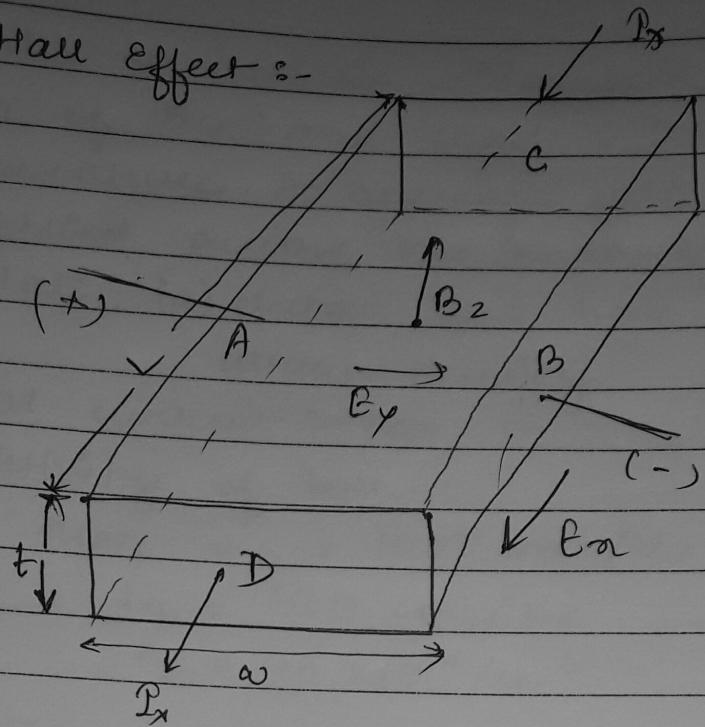
$$q = 1.6 \times 10^{-19} \text{ C.}$$

$$n_i = 2.5 \times 10^{13} \text{ cm}^{-3}$$

$$\text{conc of Ge (N_{Ge})} = 4.41 \times 10^{22}/\text{cm}^3$$

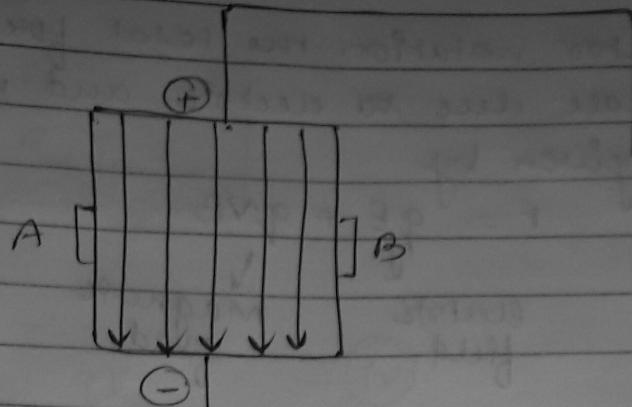
then,

⇒ The Hall Effect :-



$$V_{AB} = 0$$

$$M_F \neq 0$$



$$V_{AB} = 0.$$

→ Hall effect is the production of voltage difference across an electrical conductor, transverse to an electric current in the conductor and a magnetic field perpendicular to the current.

Pmp:

If a current flows through a conductor in the magnetic field, the magnetic field exerts a transverse force on the moving charge carriers which tends to push them on one side of conductor. This is most evident in a thin flat conductor.

A build-up of charge at the sides of the conductor will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor. The presence of this measurable transverse voltage is called the Hall Effect by E.H. Hall, who discovered this phenomenon in 1879.

Insp → Using vector notation the total force on a single hole due to electric and magnetic field is given by

$$F = q \underset{\text{Electrode}}{\cancel{E}} + q \underset{\text{magnetic}}{\cancel{v \times B}}$$

$$\Rightarrow F = q(E + v \times B) \quad \text{--- (1)}$$

Total field in y-direction is given by,

$$F_y = q(E_y - v_x B_z) \quad \text{--- (11)}$$

Now

→ From eqn (11), product of  $q$ ,  $q v_x B_z$  tends the hole to be y-direction. However to maintain steady state flow of holes down the length of the bar, electric field  $E_y$  must be balanced by  $v_x B_z$

$$E_y = v_x B_z \quad \text{--- (111)}$$

→ Hence, net force  $F_y$  is zero, as  $E_y$  becomes  $v_x B_z$ , no net lateral force is experienced by the holes as they drift along the bar. The establishment of electric field  $E_y$  is called Hall effect and resulting voltage

$$V_{AB} = E_y w \text{ is called Hall voltage.}$$

Through the eqn of drift velocity, we have,

$$E_y = \frac{f_m B_z}{qP_0}$$

$$\Rightarrow E_y = R_H f_m B_z$$

where

$$R_H = \frac{1}{qP_0} - \textcircled{V}$$

→ Hall field is proportional to product of current density and magnetic flux density with a proportionality constant,  $R_H$  given by  $\frac{1}{qP_0}$  called the Hall coefficient.

$$\text{Again Hall concentration } P_0 = \frac{1}{qR_H} = \frac{qE_y}{qP_0 \omega t B_z}$$

$$\begin{aligned} &= \left( \frac{q}{P_0 \omega t} \right) B_z \\ &\quad q \left( V_{A0} / \omega \right) \\ \Rightarrow P_0 &= \frac{B_z}{q \tau V_{A0}} \quad \textcircled{V} \end{aligned}$$

→ RHS of eqn  $\textcircled{V}$  can be measured and finally carrier concentration can be calculated.

$$\rightarrow \text{Sample resistivity can be given by} \\ \rho (\Omega \cdot \text{cm}) = R_{WT} = \frac{V_{ED}}{I_{WT}} \quad \textcircled{W}$$

→ Conductivity is given by,

$$\sigma = \frac{1}{p} = q n_p p_0$$

The mobility  $n_p$  is ratio of Hall coefficient and resistivity.

$$n_p = \frac{R_H}{p}$$

(VII)

Q.

Consider a semiconductor bar with  $w = 0.1 \text{ mm}$ ,  
 $t = 10 \mu\text{m}$ ,  $L = 5 \text{ mm}$  for  $B = 10 \text{ KG}$   
( $1 \text{ KG} = 10^{-5} \text{ wb/cm}^2$  or Tesla) in the direction shown in the diagram. A current of  $1 \text{ mA}$  we have  $V_{AB} = -2 \text{ mV}$  and  $V_{CD} = 100 \text{ mV}$ ,  
Find time, concentration and mobility of majority carriers.