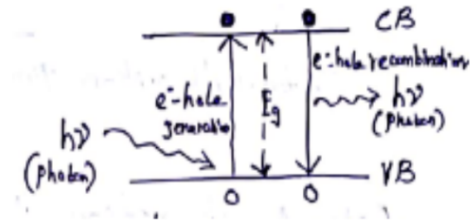


# 1. What do you mean by Band to band and impurity to band transition in semiconductors?

## 1. Band to band transition (Inter band transition)

An absorbed photon can result in an electron in the valence band making an upward transition to conduction band. This results electron-hole pair generation, followed by this electron-hole recombination takes place by the emission of Photon

Eg: Band to Band transition in GaAs can results absorption and emission of photons with wavelength of 0.87  $\mu\text{m}$  or ( $E_g = 1.42 \text{ eV}$ )



## 2. Define optical absorption process in semiconductor with diagram.

Optical absorption process :

Absorption is the process in which the photons are absorbed by the semiconductor materials causes transition of electron from valence band to conduction band.

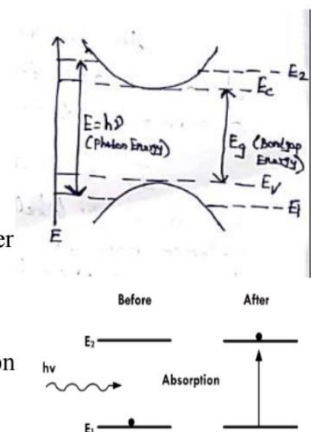
Consider direct band to band absorption

The condition for absorption to happen, the incident photon energy must be equal Or greater than the bandgap i.e  $h\nu \geq E_g$ , corresponding wavelength  $\lambda = hc/E_g$ .

The electron hole pairs are generated due to absorption of photon having energy greater Or equal to bandgap.

This leads to the increase of concentration of mobile charge carriers and increase the Conductivity of the material.

So the material behaves as a photoconductor with a conductivity proportional to photon Flux, the effect is used to detect light.



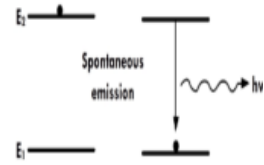
## 3. Define the types of optical emission process with diagrams.

### Emission process:

Generally the emission process takes place in two types in optical devices

1. Spontaneous emission
2. Stimulated emission

**Spontaneous emission:** spontaneous emission, this process requires a conduction band energy state occupied by an electron and an empty valence band energy state. The electron itself transits from conduction band to valence band spontaneously by releasing a photon.



This photon has a random direction and phase.

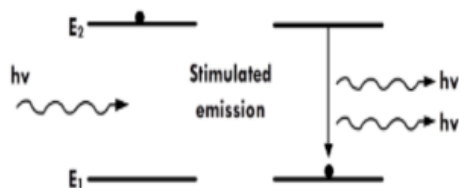
This is the opposite of the common situation in equilibrium, but at a finite temperature there will be a small number of full states in the conduction band and empty states in the valence band. Also, electrons and holes can be created via optical absorption and other pumping mechanisms.



### Stimulated emission:

An incident photon causes an upper level atom to decay, emitting a "stimulated" photon whose properties are identical to those of the incident photon.

The term "stimulated" underlines the fact that this kind of radiation only occurs if an incident photon is present



**4. What is the Optical recombination process? Write three optical properties in which the optical recombination process is observed.**

Recombination electron – hole pairs observed in different optical process

- Luminescence: Process where electron hole pairs created and recombined radiatively
- Photoluminescence: electron- hole pairs are generated due to absorption of light and recombination occurs radiatively
- Cathodoluminescence: electron – hole pairs are generated by the electron bombardment, and radiative recombination occurs
- Electroluminescence: process of radiative recombination following injection with pn-junction or similar device.

- When a semiconductor is illuminated with light an electron in the valence band making an upward transition to conduction band.
- This results electron-hole pair generated, the reverse process of electron-hole annihilation is called recombination.
- Recombination process may be radiative or non- radiative
  1. If electron annihilated with hole energy is released equal to  $E \geq E_g$  called radiative recombination, in this process a photon of energy  $E = h\nu$  is released
  2. If electron annihilated with hole energy is released equal to  $E < E_g$  called non radiative recombination, in this process phonons are released

**5. Using the relation  $N_1 Q_{B12} = N_2 A_{21} + N_2 Q_{B21}$ , derive the expression for ratio between spontaneous and stimulated coefficient.**

## Ratio between Spontaneous and Stimulated Coefficient

For a given system under equilibrium

Absorption = Emission (Spontaneous + Stimulated)

$$N_1 B_{12} = N_2 A_{21} + N_2 B_{21}$$

$$\text{Then } Q = \frac{A_{21}}{\left[\frac{N_1}{N_2}\right] B_{12} - B_{21}} \rightarrow (1)$$

From Boltzmann distribution law, at a given temperature ( $T$ ), the ratio of population of two levels is given by

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/kT} = e^{h\nu/kT} \Rightarrow Q = \frac{A_{21}}{e^{h\nu/kT} B_{12} - B_{21}} \rightarrow (2)$$

Also, from Planck's body radiation theory

$$Q = \frac{8\pi h c}{\lambda^5} \times \left[ \frac{1}{e^{h\nu/kT} - 1} \right] \rightarrow (3)$$

In equation (2) if  $B_{21} = B_{12}$  then  $Q = \frac{A_{21}}{B_{21}} \times \left[ \frac{1}{e^{h\nu/kT} - 1} \right] \rightarrow (4)$

Comparing (3) & (4) we write  $\frac{A_{21}}{B_{21}} = \frac{8\pi h c}{\lambda^5}$

Here  $A$  &  $B$  are Einstein's Coefficients which gives value for ratio of Spontaneous and Stimulated emission.

**6. What is the optical joint density of states? Write the expression for finding optical joint density of states and state how it is related with energy band gap of materials.**

### **Optical Joint Density of States**

How many states are possible for photon interaction of energy  $h\nu$  in valence and conduction band is given by optical joint density of states. To determine the density of state  $\rho(\gamma)$  with which a photon of energy  $h\nu$  interacts under a condition of energy and momentum conservation in a direct band gap semiconductor.

To approximate this relation for a direct band-gap semiconductor by two parabolas,

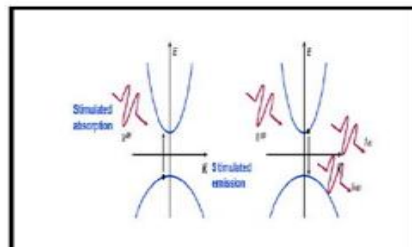
$$E_2 = E_c + \frac{\hbar^2 K^2}{2m_c}$$

$$E_1 = E_v - \frac{\hbar^2 K^2}{2m_v}$$

$$h\nu = E_2 - E_1$$

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

$$K^2 = \frac{2m_v}{\hbar^2} (h\nu - E_g)$$



Here, substitute the value of  $K^2$  in eq (1) & eq (2)

$$E_2 = E_c + \frac{m_v}{m_c} (h\gamma - E_g)$$

Similarly,

$$E_1 = E_v - \frac{m_v}{m_c} (h\gamma - E_g)$$

The one-to-one correspondence between  $E_2$  and  $\gamma$  permits us to readily relate  $\rho(\gamma)$  to the density of states  $\rho_c(E_2)$  in conduction band by use of the incremental relation

$$\rho_c(E_2)dE = \rho(\gamma) d\gamma$$

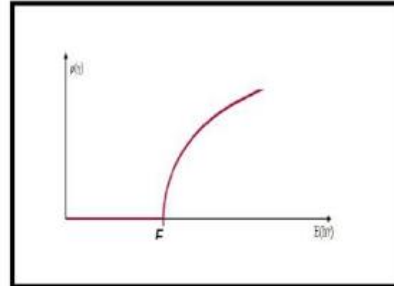
Here  $\rho_c(E_2)dE$  is no of states between  $E_2$  and  $dE_2$  and  $\rho(\gamma) d\gamma$  is the number of states per unit volume of energy between  $h\gamma$  and  $h(\gamma+d\gamma)$  to interact.

Therefore,

$$\rho(\gamma) = \rho_c(E_2) \frac{dE}{d\gamma}$$

$$\rho(\gamma) = \frac{(2m_v)^{3/2}}{\pi\hbar^2} (h\gamma - E_g)^{1/2} \text{ for } h\gamma \geq E_g$$

The density of states which a photon of energy  $h\gamma$  interact increases with  $h\gamma \geq E_g$  in accordance with a square root law. Similarly One-to-One correspondence between  $E_1$  and  $\rho(\gamma)$  in equation, together with  $\rho(\gamma) E_1$ , results in an expression for  $\rho(\gamma)$  identical.



**7.What is Density of states for photons? Write the expression to find density of state for photons in-terms of energy and frequency.**



## Density of States for Photons:

⇒ Total number of states/Volume

⇒ Das for Photons → Total number of allowed states/unit volume in energy range  $E$  to  $E+dE$



$$\text{Density } P(E) = \frac{dn(E)}{dE} \quad \text{--- (1)}$$

$n(E)$  → Number of Photons in phase-space having 'E'

$dn(E)$  → • of Photons in infinitesimal small phase having Energy  $E$  to  $E+dE$

$P(E)$  → density of states of Photon

Phase-space ⇒ It is a hypothetical space [ 6 dimensional space with position and momentum ]

$$3 + 3 = 6 \text{ Coordinates}$$

$$(x, y, z) (p_x, p_y, p_z)$$

Volume of phase space  $h^3$

Number of photons in an infinitesimal small Volume is given by,

$$dn(E) = \frac{d^3r d^3p}{h^3} \quad \text{--- (2)}$$

Phase space with  $h^3$  volume



$$1 \text{ Cell Volume} = h^3$$

$$dn(E) \Rightarrow \text{Total Cells, } \frac{dn(E)}{h^3}$$

$$\therefore \text{Total Volume} = h^3 \cdot dn(E)$$

$$\text{But Total Volume} = d^3r d^3p$$

If 'n' number of photons in 1 volume mean total no. of volume =  $n \cdot h^3$

Total number of photons in entire space,

$$n(E) = \int dn(E) = \int \frac{dr^3 dp^3}{h^3}$$

$$dr^3 = dx \cdot dy \cdot dz = V$$

$$= \frac{V}{h^3} \int dp^3 \quad - (3)$$

To understand, momentum coordinate integration, we should utilize Spherical polar coordinates,  $(r, \theta, \phi) \Rightarrow (p, \theta, \phi)$

$$\int d^3p = \iiint p^2 dp \sin \theta d\theta \cdot d\phi \quad - (4)$$

Angle  $\Rightarrow 0$  to  $2\pi$

$-1(-1) + 1$

$$\begin{aligned} &= \int_0^{2\pi} d\phi \int_0^{2\pi} \sin \theta d\theta \cdot \int_{p_1}^{p_2} p^2 dp \\ &= (\phi)_0^{2\pi} \cdot (-\cos \theta)_0^{2\pi} \cdot \int_{p_1}^{p_2} p^2 dp \\ &= (2\pi) (2) \cdot \int_{p_1}^{p_2} p^2 dp = 4\pi \int_{p_1}^{p_2} p^2 dp \end{aligned}$$



Back into the eqn. (3)

$$\begin{aligned} E &= mc^2 \\ &= mc \cdot c \\ E &= p \cdot c \\ p &= \frac{E}{c} \end{aligned}$$

According to Pauli,  
a photon has two states of  
polarization,

$$\begin{aligned} n(E) &= \frac{V}{h^3} \int dp^3 \\ &= \frac{V}{h^3} \cdot 4\pi \int p^2 dp \\ &= \frac{4\pi \cdot V}{h^3} \int \frac{E^2}{c^2} \cdot \frac{dE}{c} \\ &= \frac{4\pi \cdot V}{h^3 c^3} \left( \frac{E^3}{3} \right) \\ &= \frac{4\pi \cdot V \cdot E^3}{3h^3 c^3} \\ n(E) &= 2 \times \frac{4\pi \cdot V \cdot E^3}{3h^3 c^3} = \frac{8\pi \cdot V \cdot E^3}{3h^3 c^3} \end{aligned}$$

The DOS of photons

$$P(E) = \frac{dn(E)}{dE} = \frac{d}{dE} \left( \frac{8\pi V \cdot E^3}{3h^3 c^3} \right)$$

$$= \frac{8\pi V}{3h^3 c^3} \frac{d(E^3)}{dE} = \frac{8\pi V \cdot 3E^2}{3h^3 c^3}$$

$$P(E) = \frac{8\pi \cdot V \cdot E^2}{h^3 c^3}$$

$$\begin{aligned} n(E) &\propto E^3 \\ P(E) &\propto E^2 \end{aligned}$$

We can derive the DOS in terms of frequency  $\nu$

$$E = h\nu$$

$$P(\nu) = \frac{8\pi V \cdot (h\nu)^2}{h^3 \cdot c^3} = \frac{8\pi \cdot V \cdot \nu^2}{h \cdot c^3}$$

$$\text{Similarly, } n(\nu) = \frac{8\pi \cdot V \cdot (h\nu)^3}{3h^3 c^3} = \frac{8\pi \cdot V \cdot \nu^3}{3c^3}$$

**8. Define the concept of Fermi Golden rule. Write the equation to find transition rate per unit volume of a system.**

Fermi's golden rule is a simple expression for the transition probabilities between states of a quantum system, which are subjected to a perturbation. It is used for a large variety of physical systems covering, e.g., nuclear reactions, optical transitions, or scattering of electrons in solids.

Consider a semiconductor illuminated by electromagnetic radiations (light). The interaction between photons and the electrons in the semiconductor can be described by the Hamiltonian operator.

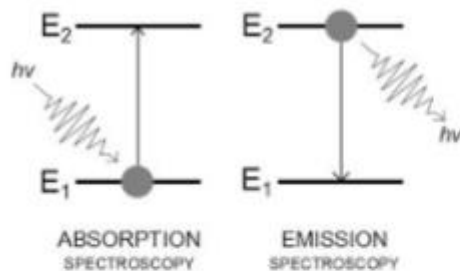
$$\vec{H} = \frac{1}{2m_0} (\vec{p} - e\vec{A})^2 + \vec{V}(r)$$

Where ,

$m_0$  is the free electron mass,  $\vec{A}$  is the vector potential accounting part of electromagnetic field.

$\vec{V}(r)$  is the periodic potential and  $e = -|e|$

## Optical Transitions Using Fermi's Golden Rule



Using the time dependent perturbation theory, the transition rate for the absorption of a photon can be derived, assuming an electron is initially at state  $E_1$  is given by Fermi's Golden rule

$$W_{abs} = \frac{2\pi}{\hbar} |\langle b | H'(r) | a \rangle|^2 \delta(E_b - E_a - \hbar\omega)$$

Where  $E_b > E_a$  is assumed.

The total upward transition rate per unit volume

Where  $E_b > E_a$  has been assumed. The total upward transition rate per unit volume ( $S^{-1}, cm^{-3}$ ) in the crystal taking into account the probability that state a is occupied and state b is empty is

$$R_{a \rightarrow b} = \frac{2}{V} \sum_{\kappa_a} \sum_{\kappa_b} \frac{2\pi}{\hbar} |H'_{ba}|^2 \delta(E_b - E_a - \hbar\omega) f_a (1 - f_b)$$



## Optical Transitions Using Fermi's Golden Rule

Where we sum over the initial and final states and assume that the Fermi-Dirac distribution  $f_a$  is the probability that the state  $a$  is occupied. A similar expression holds for  $f_b$  with  $E_a$  replaced by  $E_b$ , and  $(1 - f_b)$  is probability that the state  $b$  is empty. The prefactor 2 takes into account the sum over spins, and the matrix element  $H'_{ba}$  is given by

$$H'_{ba} = |\langle b | H'(r) | a \rangle|^2 = \int \psi^*(r) H'(r) \psi_a(r) d^3r$$

Similarly, The transition rate for the emission of a photon (fig.2) if an electron is initially at state  $b$  is.

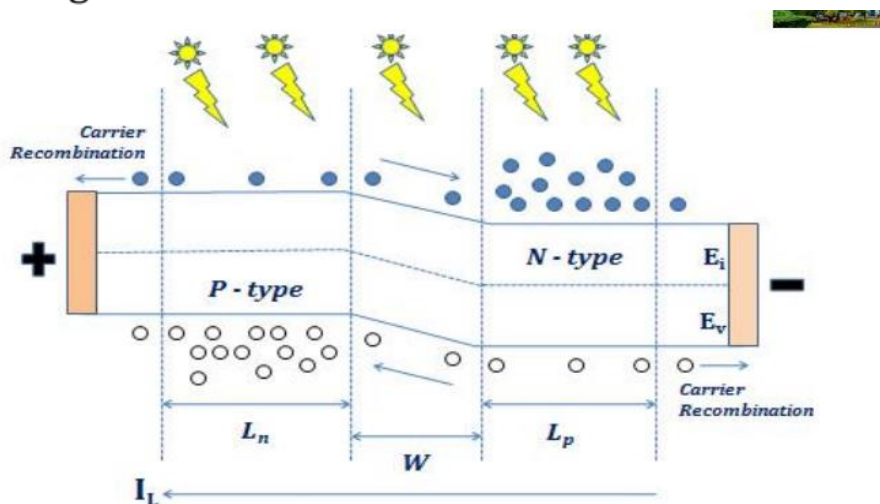
$$W_{\text{ems}} = \frac{2\pi}{\hbar} |\langle a | H'(r) | b \rangle|^2 \delta(E_a - E_b + \hbar\omega)$$

The downward transition rate per unit volume ( $\text{S}^{-1} \text{cm}^{-3}$ ) is

$$R_{b \rightarrow a} = \frac{2}{V} \sum_{K_a} \sum_{K_b} \frac{2\pi}{\hbar} |H'_{ab}|^2 \delta(E_a - E_b + \hbar\omega) f_b (1 - f_a)$$

## 9. What is the photovoltaic effect? Draw the diagram to show p-n junction under illumination.

**Photovoltaic effect:** It is a process that generates voltage or electric current in semiconductor device when it is exposed to sunlight.



$L_n$  and  $L_p$  - Diffusion length of electron and hole in Quasi neutral region,  $W$  - Width of depletion region or Space charge region,  $E_v$  - Energy of valence band and  $E_i$  - Fermi energy

## 10. Define the given terms used to find efficiency of solar cell: (i) Short circuit current, (ii) Open circuit voltage and (iii) Fill factor.

## Efficiency of a Solar Cell:

To determine the efficiency of the solar cell following parameters are to be described

### ➤ Short-Circuit Current $I_{sc}$

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited).

$$I_{sc} = -I_L \quad (8)$$

Here Short-Circuit Current is nothing but light generated current.

### ➤ Open-Circuit Voltage $V_{oc}$

The open-circuit voltage,  $V_{oc}$ , is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current.

$$V_{oc} = \frac{nkT}{q} \ln \left( 1 + \frac{I_L}{I_s} \right) \quad (9)$$

### ➤ Fill Factor FF

Fill Factor FF, is a measure of the realizable power from a solar cell. Typically, the fill factor is between 0.7 and 0.8. The FF is defined as the ratio of the maximum power from the solar cell to the product of  $V_{oc}$  and  $I_{sc}$  so that

$$FF = \frac{P_m}{I_{sc}V_{oc}} = \frac{I_m V_m}{I_{sc}V_{oc}} \quad (10)$$

**11. Determine the Open-Circuit Voltage  $V_{oc}$  of the solar cell, if Saturation Current ( $I_s$ ) =  $0.75 \times 10^{-10}$  A, Light Generated Current ( $I_L$ ) = 0.65 A, Ideality Factor ( $n$ ) = 0.9, and Temperature ( $T$ ) = 310K.  
(Answer:  $V_{oc} = 0.55V$ )**

$$\begin{aligned}
 I_L &= 0.65 \text{ A} & L_S &= 0.75 \times 10^{-10} \\
 n &= 0.9 & T &= 310 \text{ K} \\
 V_{oc} &= \frac{nKT}{q} \left[ \ln \left( 1 + \frac{I_L}{L_S} \right) \right] \\
 &\Rightarrow \frac{0.9 \times 1.38 \times 10^{-23} \times 310}{1.6 \times 10^{-19}} \ln [1 + 8.6 \times 10^9] \\
 &\Rightarrow 240.6 \times 10^{-4} \times \ln [1 + 8.6 \times 10^9] \\
 &\Rightarrow 240.6 \times 22.87 \times 10^{-4} \\
 &\Rightarrow 0.55 \text{ V}
 \end{aligned}$$

**12. Determine the Conversion Efficiency  $\eta$  of the solar cell, if Short-Circuit Current ( $I_{sc}$ ) = 3.5A, Open-Circuit Voltage ( $V_{oc}$ ) = 0.6V, Fill Factor  $FF$ ) = 0.7 and Input Power ( $P_{in}$ ) = 10W. (Answer: Conversion Efficiency  $\eta$  = 14.7%)**

$$\eta = \frac{I_{sc} V_{oc} FF}{P_{in}} \times 100\%$$

$$I_{sc} = 3.5 \text{ A}$$

$$V_{oc} = 0.6 \text{ V}$$

$$FF = 0.7$$

$$P = 10 \text{ W}$$

$$\Rightarrow \frac{3.5 \times 0.6 \times 0.7}{10} \times 100\%$$

$$\Rightarrow \frac{1.47}{10} \times 100\%$$

$$\Rightarrow 14.7\%$$

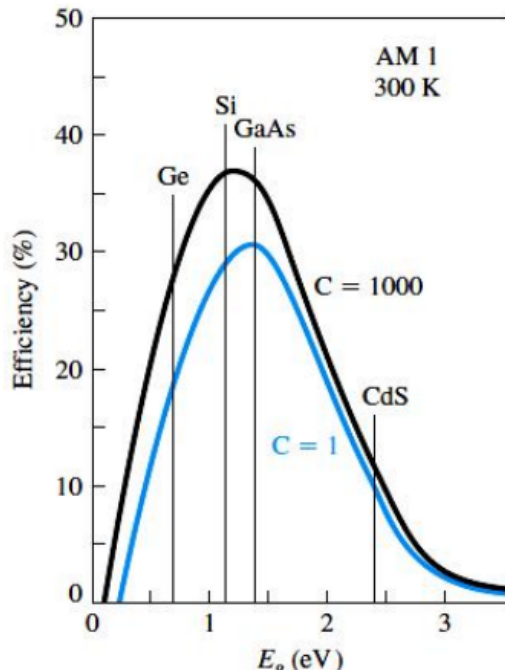
**13. Define the efficiency of solar cells. Write the expression and a plot to show variation of efficiency with band gap of materials.**

➤ **Conversion Efficiency  $\eta$**

The *conversion efficiency*  $\eta$  of a solar cell is defined as the ratio of output electrical power to incident optical power. For the maximum power output, we can write

$$\eta = \frac{P_m}{P_{in}} \times 100\% = \frac{I_m V_m}{P_{in}} \times 100\% = \frac{I_{sc} V_{oc} FF}{P_{in}} \times 100\% \quad (11)$$

The maximum possible current density and the maximum possible voltage in the solar cell are  $I_{sc}$  and  $V_{oc}$ , respectively.



**Figure 4** | Ideal solar cell efficiency at  $T = 300$  K for  $C = 1$  sun and for a  $C = 1000$  sun concentrations as a function of bandgap energy.

**14. Define any three losses which decrease the efficiency of solar cell.**

**Loss in Solar Cell : Factors which affect Efficiency of the Solar Cell**

1. Loss due to Low Energy Photons ( $h\nu < E_g$ )
2. Loss due to High Energy Photons ( $h\nu > E_g$ )
3. Voltage Loss
4. Fill Factor Loss
5. Loss due to Reflection
6. Loss due to less Absorption
7. Loss due to covering of Metal Contact
8. Recombination Loss

**15. Make a short note on postulates of Drude model for electrical conductivity of material.**



## Drude Theory

In Drude model, when atoms of a metallic element are brought together to form a metal, the valence electrons from each atom become detached and wander freely through the metal, while the metallic ions remain intact and play the role of the immobile positive particles.

Electrons in a metal behave much like particles in an ideal gas (no Coulombic interaction and no collisions between particles).

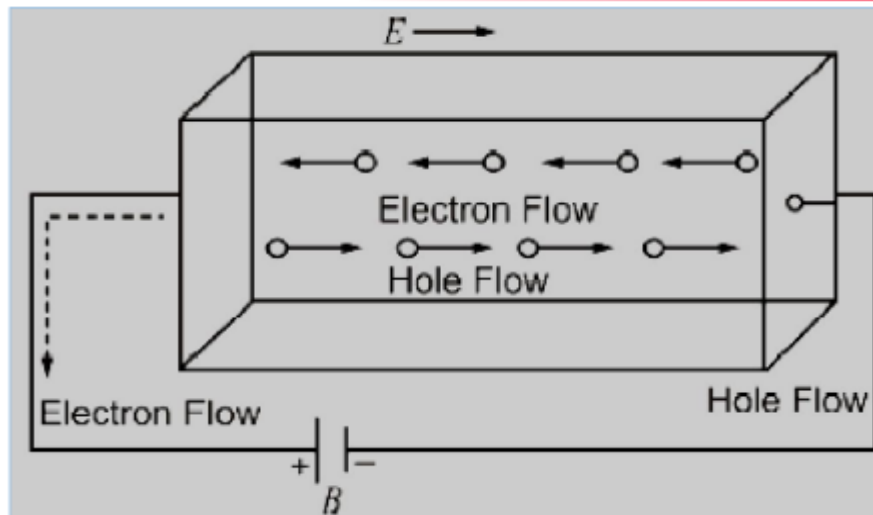
Some of these electrons ' $Z$ ', are the relatively weakly bound valence electrons. The remaining ( $Z_a - Z$ ) electrons are relatively tightly bound to the nucleus and are known as the *core electrons*.

These isolated atoms condense to form the metallic ion, and the valence electrons are allowed to wander far away from their parent atoms. They are called '*conduction electron gas*' or '*conduction electron cloud*'.

Due to kinetic theory of gas Drude assumed, conduction electrons of mass ' $m$ ' move against a background of heavy immobile ions.

>>Determination of Electrical Conductivity of Semiconductor<<

To determine electrical conductivity by applying Drude theory, we consider a rectangular bar of intrinsic semiconductor connected to a battery as shown in Fig. 1. If the direction of electric field is along x-direction then the free electrons will accelerate along negative x-axis and holes along x-direction. So, the velocity of electrons along negative x-direction increases and attains some constant resultant velocity. This constant velocity is called drift velocity, represented as  $V_d$



The total electrical current through the semiconductor is the sum of electron current  $I_e$  and hole current  $I_h$

To find the expression for electrical conductivity, consider a rectangular bar of length  $L$  and cross-section area  $A$ . Let ' $n$ ' be the number of electrons per unit volume of the semiconductor i.e. its electron density, and  $E$  be the applied electric field. Due to this applied electric field, let  $V_d$  be the average or drift velocity of the electrons. Assume a plane perpendicular to cross sectional area  $A$ . Then the number of electrons crossing the imaginary plane in 1 second is  $nAV_d$

## 16. Define the term (i) Drift Velocity, (ii) Relaxation time of electron. Write the expression to find electrical conductivity using Drude model.

In the presence of externally applied electromagnetic fields, the electrons acquire some amount of energy from the field and are directed to move towards higher potential. As a result, the electrons acquire a constant velocity known as *Drift velocity  $V_d$* .

The time ' $\tau$ ' is known as the relaxation time and it is defined as the time taken by an electron between two successive collisions. That relaxation time is also called *mean free time* [or] *collision time*.

Then the current flowing across the plane is

$$I_e = neAV_d \quad (2)$$

Then the electron current density is,

$$J_e = \frac{I_e}{A} = neV_d \quad (3)$$

From Ohm's law, the current density  $J_e$  due to electrons is given as

$$\begin{aligned} V &= IR = \frac{IL\rho}{A} \\ \frac{I}{A} &= J_e = \frac{V}{L\rho} = E\sigma_n \end{aligned} \quad (4)$$

Here electrical conductivity of electrons.

From eqn. 3 and eqn. 4, we have

$$J_e = neV_d = E\sigma_n \quad (5)$$

The drift velocity produced per unit applied electric field is called the mobility of electrons represented as

Or 
$$\mu_e = \frac{V_d}{E}$$

$$V_d = \mu_e E \quad (6)$$

Substituting eqn. 6 in eqn. 5 gives

$$\sigma_n = ne\mu_e \quad (7)$$

Eqn. 7 represents electrical conductivity due to electrons.

Similarly, the electrical conductivity of holes can be obtained.

Let  $p$  be the number of holes per unit volume of the material,  $\mu_h$  is the mobility of holes and the charge of a hole is ' $e$ ', then

$$\sigma_p = pe\mu_h \quad (8)$$

The total conductivity of an intrinsic semiconductor is given by the sum of eqn. 7 and eqn. 8.

$$\sigma = \sigma_n + \sigma_p = ne\mu_e + pe\mu_h$$

$$\sigma = ne[\mu_e + \mu_h] \quad (9)$$

**17. Determine the Conductivity ( $\sigma$ ) of the Intrinsic Semiconductor. The given parameters are:  $\mu_e = 0.145 \text{ m}^2/\text{V-s}$ ;  $\mu_h = 0.055 \text{ m}^2/\text{V-s}$ ;  $n_i = 1.5625 \times 10^{16} \text{ /m}^3$ ;  $q = 1.602 \times 10^{-19} \text{ C}$ . (Answer:  $5 \times 10^{-4} \text{ mhos/m}$ ).**

Handwritten solution for problem 17:

$$\begin{aligned} \mu_e &= 0.145 \frac{\text{m}^2}{\text{V-s}} & \mu_h &= 0.055 \frac{\text{m}^2}{\text{V-s}} \\ n_i &= 1.5625 \times 10^{16} \frac{1}{\text{m}^3} & q &= 1.602 \times 10^{-19} \text{ C} \end{aligned}$$
$$\sigma = ne[\mu_e + \mu_h]$$
$$\Rightarrow 1.5625 \times 10^{16} \times 1.602 \times 10^{-19} [0.145 + 0.055]$$
$$\Rightarrow 2.5 \times 10^{-3} \times 2 \times 10^{-1}$$
$$\Rightarrow 5 \times 10^{-4} \frac{\text{mho}}{\text{m}}$$