

# PAPER SOLUTION

## WINTER 2023

**Subject code : 3110018**

**Subject Name : Physics**

**Q-1 (a) Mention any three postulates of classical free electron theory proposed by Lorents and Drude.**

- Ans :**
- 1) It explains the electrical conductivity and thermal conductivity of metals.
  - 2) It explains the Wiedemann - Franz law.
  - 3) It verifies Ohm's law.

**(b) (i) State any two points of differences between intrinsic and extrinsic semiconductors.**

**(ii) State any two points of differences between n-type and p-type semiconductors.**

**Ans :**

(i) Differences between intrinsic and extrinsic semiconductors.

Parameter	Intrinsic Semiconductor	Extrinsic Conductor
Conductivity	The electrical conductivity of intrinsic semiconductors is low.	The extrinsic semiconductors have high electrical conductivity.
Dependency of conductivity	The conductivity of intrinsic semiconductor is dependent on temperature only.	The conductivity of extrinsic semiconductor is dependent on temperature as well as amount of impurity added.

(ii) Differences between n-type and p-type semiconductors.

SR. NO	p-type	n-type
1.	Number of holes are more than the number of electrons	Number of electrons are more than the number of holes.
2.	Trivalent impurities are used for doping	Number of electrons are more than the number of holes.
3.	These are called as acceptors	These are called as doners
4.	Holes are majority charge carriers.	Electrons are majority charge carriers.

**(c) What is superconductivity? Discuss any three properties of superconductors in detail.**

**Ans :** Superconductivity is a phenomenon observed in certain materials where they exhibit zero electrical resistance and the expulsion of magnetic fields when cooled below a characteristic critical temperature. This critical temperature varies depending on the material and is a key property of superconductors.

→ Properties of super conductors:-

### **Property 1: Critical temperature/Transition temperature**

→ The temperature below which the material changes from conductors to superconductors is called critical temperature or transition temperature. The transition from conductors to superconductors is sudden and complete.

**Property 2: Zero Electric Resistance/Infinite Conductivity**

→ In the superconducting state, the material has zero resistance. When the temperature of the material is reduced below the critical temperature, its resistance suddenly reduces to zero. Mercury is an example of a superconductor that shows zero resistance below 4 kelvin.

**Property 3: Expulsion of Magnetic Field**

→ Below the critical temperature, superconductors do not allow the magnetic field to penetrate inside it. This phenomenon is called Meissner Effect.

**Property 4: Critical Magnetic Field**

→ The certain value of the magnetic field beyond which the superconductors return to conducting state is called the critical magnetic field. The value of the critical magnetic field is inversely proportional to the temperature. As the temperature increases, the value of the critical magnetic field decreases.

**Q-2 (a) Obtain Fermi factor  $f(E)$  for energy 0.01 eV above Fermi energy ( $E_f$ ) at 500 K.**

**Ans :**

→ Given :-

$$E - E_f = 0.001 \text{ eV}$$

$$T = 200 \text{ K}$$

→ From Fermi-Dirac distribution:-

$$F(E) = \frac{1}{1 + e^{\frac{E - E_f}{k_B T}}}$$

$$F(E) = \frac{1}{1 + e^{\frac{0.01 \text{ eV}}{8.617 \times 10^{-5} \times 500}}}$$

$$F(E) = \frac{1}{1 + e^{0.232}}$$

$$= \frac{1}{1 + 1.2611}$$

$$= \frac{1}{2.611}$$

$$F(E) = 0.4422$$

**(b) State and discuss Wiedemann-Franz law.**

**Ans :**

According to the Wiedemann-Franz law

→ The ratio of the thermal conductivity of the material and the electrical conductivity of the material is directly relative to the temperature.

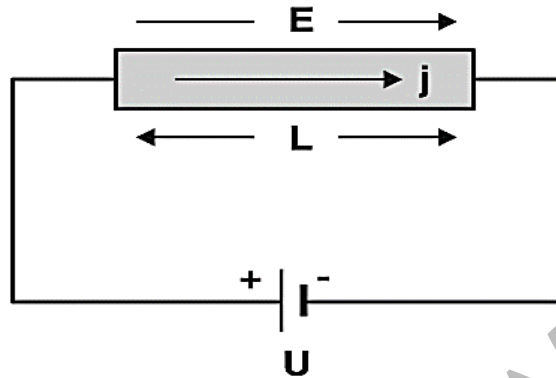
→ The Wiedemann-Franz law is one of the fundamental laws in physics. This law was proposed in the year 1835 and is named after German physicists, Gustav Wiedemann and Rudolph Franz.

Gustav Wiedemann discovered that thermal conductivity ( $\kappa$ ) and the electrical conductivity ( $\sigma$ ) are approximately have same value at the same temperature for different metals

→ In this law:

→ Thermal Conductivity ( $\kappa$ ) is the degree of the capacity of a material to conduct heat.

→ Electrical Conductivity ( $\sigma$ ) is the degree of the capacity of a material to conduct electricity  $\frac{1}{\rho}$ .



### Wiedemann-Franz Law Model

→ The law states that the ratio of the electronic contribution of the thermal conductivity ( $\kappa$ ) to the electrical conductivity ( $\sigma$ ) of metal is somewhat equivalent to the temperature ( $T$ ).

$$\frac{\kappa}{\sigma} = LT$$

→ Here, the  $L$  is the proportionality constant, and it is called the Lorenz number. The  $L$  is equal to:

$$L = \frac{\kappa}{\sigma T} = \frac{\pi^2}{3} \left( \frac{\kappa_B}{e} \right)^2 = 2.44 \times 10^{-8} \text{ W}\Omega\text{K}^{-2}$$

→ The relationship between the thermal and electrical conductivity is based on the fact that heat and electrical movement involves freely moving electrons in the metal.

→ The Wiedemann-Franz law is based upon the fact that the heat and electrical transport both involve the free electrons in the metal. It also shows that with increase in particle velocity the electrical conductivity decreases and the thermal conductivity increases with the average particle velocity.

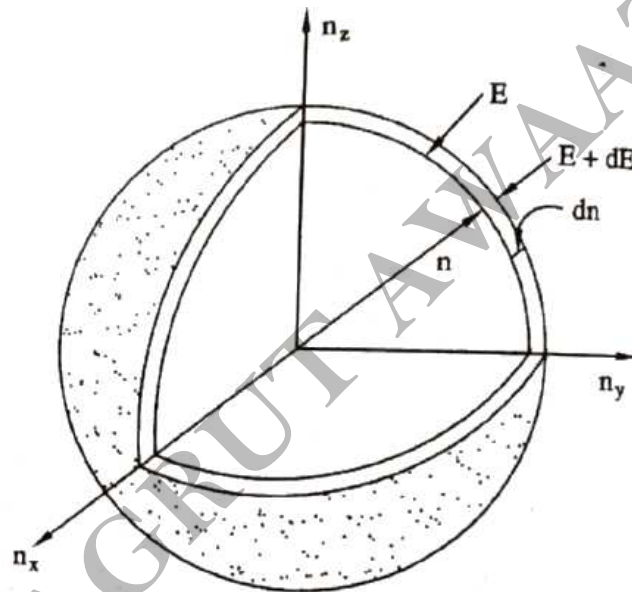
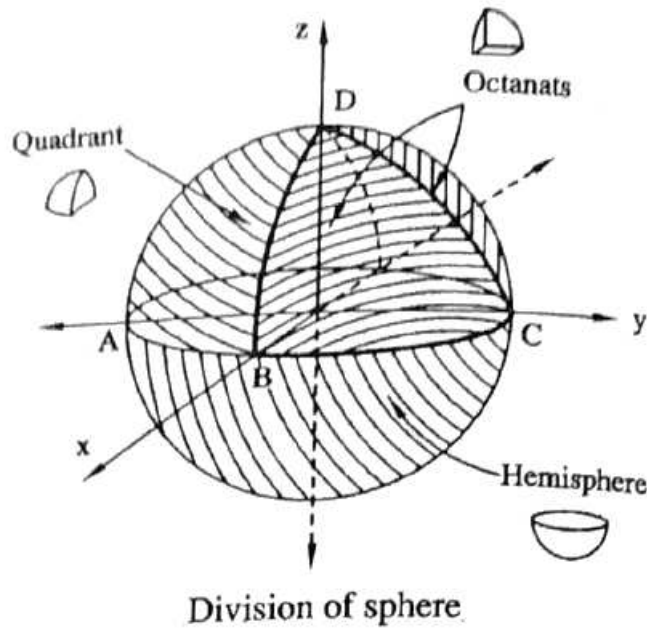
### Wiedemann Franz Law Limitations

1. The value of Lorenz number  $L$  will not remain the same for all materials.
2. The law doesn't hold true for intermediate temperature.
3. The temperature decreases as both ( $\kappa$ ) and ( $\sigma$ ) increases in the pure metals.

### (c) Define density of states and derive its expression.

**Ans :** The density of states (DOS) is essentially the number of different states at a particular energy level that electrons are allowed to occupy, i.e. the number of electron states per unit volume per unit energy.

→ Density of state  $Z(E) dE$  is defined as the number of energy states  $N(E) dE$  per unit volume in an energy interval  $dE$ .



### SPHERES SHOWING DENSITY OF STATES IN n-SPACE

$$\text{Density of states } Z(E)dE = \frac{\text{No. of energy state } N(E)dE}{\text{Unit volume of the specimen}} \quad \text{----- (1)}$$

- Consider that the sphere is further divided into number shells as shown in Fig.
- Therefore, each shell is represented by a set of quantum numbers ( $n_x, n_y, \text{ and } n_z$ ) and will have an associated energy.
- Let  $E$  be the energy of the point which is same for all points present on the sphere. Therefore, the radius of the sphere with energy  $E$  is

$$n^2 = n_x^2 + n_y^2 + n_z^2 \quad \text{----- (2)}$$

- Consider a sphere in n-space. Associated with this sphere volume will be

$$= \frac{4}{3} \pi n^3$$

→ Equation (2) represents the total volume of the sphere. We know that the quantum number  $n_x, n_y, n_z$  takes only the positive integral values and hence, one has to take only one octant in the sphere i.e.,  $1/8$  of the total volume of the sphere.

→ Therefore, the every states available within one octant of the sphere of radius  $n$  and its energy  $E$  is

$$= \frac{1}{8} \left[ \frac{4}{3} \pi n^3 \right] \text{-----(3)}$$

→ Similarly, the energy states available within one octant of the sphere of radius  $n + dn$  and its energy  $E + dE$  is

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

→ Therefore, the number of energy states available within the sphere of radius  $n$  and  $n + dn$  obtained by finding the energy difference between the two energy levels namely  $E$  and  $E + dE$ .

$$N(E)dE = (E + dE) - (E)$$

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

Expanding  $(n + dn)^3$ , we get,

$$N(E)d(E) = \frac{\pi}{6} (n^3 + 3n^2 dn + 3ndn^2 - n^3) \text{-----(5)}$$

→ Simplifying the above equation (5) using

$$(a + b)^3 = a^3 + b^3 + 3a^2b + 3ab^2, \text{ we get, } N(E)d(E) = \frac{\pi}{6} (dn^3 + 3n^2 dn + 3ndn^2)$$

→ Neglecting the higher powers of  $dn$  i.e.,  $dn^2$  and  $dn^3$ , we get

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

→ Simplify the above equation, we get,

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

$$\therefore N(E)dE = \frac{\pi}{2} n(ndn) \text{-----(7)}$$

→ Consider a cubic metal piece with cube edge  $a$ , Therefore, the energy of electron within the cube is,

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

→ Rearranging the above equation , we get,

$$n^2 = \frac{8ma^2}{h^2} dE \quad \text{----- (8)}$$

$$n = \sqrt{\frac{8ma^2}{h^2}} \quad \text{----- (9)}$$

→ The value of  $n dn$  is obtained by differentiating equation (9) , we get

$$2n dn = \frac{8ma^2}{h^2} dE \quad \text{----- (10)}$$

$$\therefore n dn = \frac{8ma^2}{2h^2} dE \quad \text{----- (11)}$$

→ Substituting the value of  $n$  and  $n dn$  from the equation (10) and (11) in equation (7) we get ,

$$N(E) dE = \frac{\pi}{2} \left( \frac{8ma^2 E}{h^2} \right)^{\frac{1}{2}} \left( \frac{8ma^2}{2h^2} \right) dE$$

→ Simplifying the above equation , we get,

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

Where ,  $a^3$  is the volume of the metal piece.

→ According to pauli's exclusion principle , we know that two electrons with opposite spin occupy each state. Therefore, the number of energy states available for electron occupancy is

$$N(E) dE = 2 \times \frac{\pi}{4} (E)^{\frac{1}{2}} \left( \frac{8m}{h^2} \right)^{\frac{3}{2}} dE \quad [\because \text{unit volume } a^3 = 1] \quad \text{----- (12)}$$

→ Equation (12) is the effective number of energy states in a volume  $a^3$  with energy between  $E$  and  $E + dB$  The number of available energy states per unit volume  $a^3 = 1$ .

→ We know that,

$$\text{Density of states} \quad Z(E) d(E) = \frac{N(E) dE}{V}$$

→ Substituting the value of  $N(E) d(E)$  and  $V = a^3 = 1$ , in the above equation , we get ,

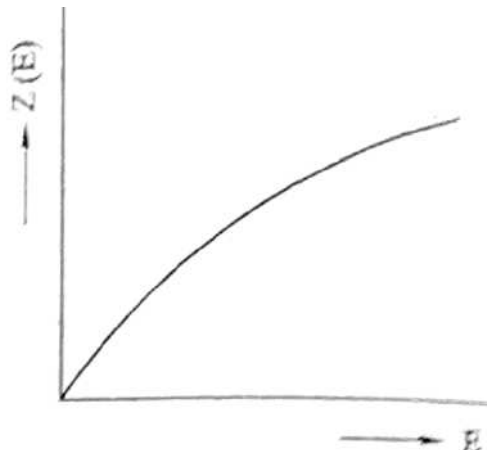
$$\text{Density of states} \quad Z(E) dE = \frac{\pi}{4} (E)^{\frac{1}{2}} \left( \frac{8m}{h^2} \right)^{\frac{3}{2}} dE \quad \text{----- (13)}$$

→ Equation (13) is the density of energy states , charge carrier in the energy interval  $E$  and  $E + dE$ . One can determine the carrier concentration in the metals and semiconductors using the above equation.

→ From equation (13) , we get

$$Z(E) \propto E^{\frac{1}{2}}$$

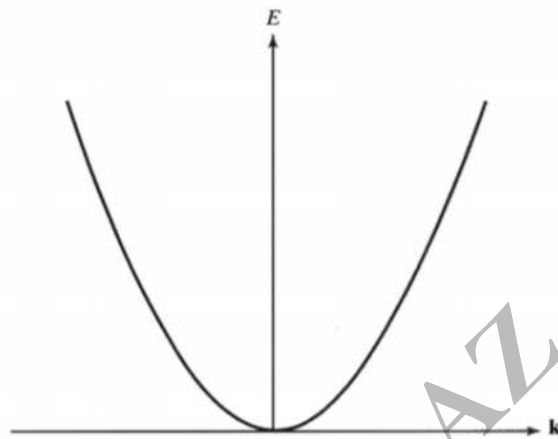
→



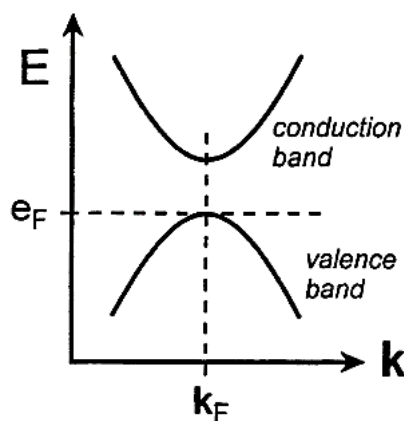
**(c) What is E-k diagram? Discuss direct and indirect band gap semiconductors based on E-k diagram**

**Ans :**

- Using energy equations for free and bound electrons from K.P.Model theory , we can draw a diagram of energy(E) Vs wave vector(k) for an electron.
- Below fig represents E - k Diagram for free and bound electrons.

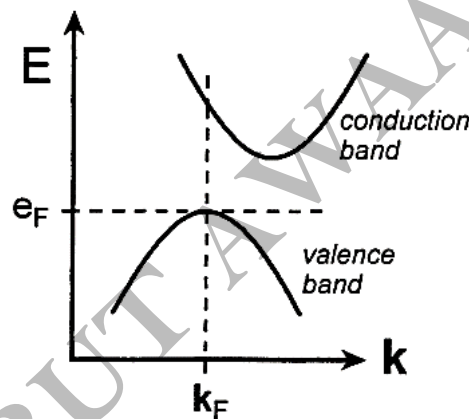


- E - k diagram for the free electron is continuous curve as free electron can have any value of energy.
- E - k diagram for bound electron is discontinuous curve as certain values of energy are forbidden as concluded in K.P.Model.
- E - k diagram provides important characteristics of any semi conducting material.
- From an E-k diagram of any semi conducting material , we may able to decide whether its direct or indirect band gap semiconductor.
- Direct Band Gap Semiconductor :



- Fig. shows reduced zone of an E-k diagram for direct band gap semiconductors.
- Upper band shows conduction band energy levels and lower band shows valence band energy levels.

- Materials for which maximum of valence band and minimum of conduction band lie for same value of  $k$ , called direct bandgap materials
- same value of wave vector leads to same values of momentum as ( $p=\hbar k$ ).
- Hence law of conservation of momentum is obeyed while transition of an electron from conduction band to the valence band.
- This direct transition produces radiative emission in terms of photon.
- Hence , Direct band gap semiconducting materials are used for optoelectronic devices like LED,Laser etc...
- Direct band gap transition occurs in time less than that of the Indirect one.  
E.g : InAs , InGaAs , GaN
- Indirect Band Gap Semiconductor :



- Fig. shows reduced zone of an E-k diagram for indirect band gap semiconductors.
- Upper band shows conduction band energy levels and lower band shows valence band energy levels.
- Materials for which maximum of valence band and minimum of conduction band do not occur at same value of  $k$ , called indirect bandgap materials.
- Hence law of conservation of momentum can not be satisfied while direct transition of an electron from conduction band to the valence band.
- A phonon assistance is required for an indirect transition of an electron.
- Hence doping of any other material is required and then transition of an electron can be possible through intermediate state.
- Emitted energy for the Indirect transition of an electron is non radiative.
- Hence , Indirect band gap semiconducting materials are used to prepare non radiative devices like PN diode,Zener diode etc...



→ Indirect band gap transition takes more time than that of the direct one.

E.g. : Si , Ge

**Q-3 (a) (i) Write fermi distribution function and mention physical significance of it.  
(ii) Mention any two applications of solar cell.**

**Ans :**

(i)

- Each energy band in a crystal accommodates a large number of electron energy levels. According to Pauli's exclusion principle any energy level can be occupied by two electrons only, one spin up and down. however, all the available energy states are not filled in an energy band.
- The separation between the consecutive energy level is very small around 10<sup>-27</sup>eV due to which the energy states are not filled in an energy band.

#### **FERMI DIRAC DISTRIBUTION FUNCTION.**

- The carrier occupancy of the energy states is represented by a continuous distribution function known as the Fermi-Dirac distribution function, given by

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

- This indicates the probability that a particular quantum state at the energy level E is occupied by an electron. Here k is Boltzmann's constant and T is absolute temperature of the semiconductor. The energy E<sub>F</sub> is called Fermi energy that corresponds to a reference level called Fermi level.

#### **FERMI LEVEL**

- Fermi level is not an allowed energy level it is an imaginary reference level used to specify other energy levels. Fermi level is defined as the highest filled energy level in any solid at absolute zero temperature.
- Hence, at absolute zero temperature all energy levels below E are empty for which the probability of occupancy can be written from Fermi-Dirac distribution function.

(ii) Applications of solar cell.

- Application of Solar Cells
- It's mostly use in the field of toys, watches, etc.
- They also use in the field of electric fence.
- It's also use in the field of Remote lighting systems area.
- This may be use in the field of portable power supplies
- They mostly use in the field of satellites.
- They also use in the field of water treatment & pumping.
- It's may be use in the field of emergency power.

**(b) Derive formula of drift and diffusion current densities.**

**Ans :**

- In any semiconductor, there is the presence of the concentration of electrons or holes. The difference in this concentration of electrons or holes is referred to as a concentration gradient. Diffusion current density is proportional to the concentration gradient.

- If the value of the concentration gradient is high then the density will be high. If concentration gradient value is low in that case diffusion density will also be low.
- Equations in between concentration gradients and the densities can be written as  
 (1) The equation for diffusion current density and concentration gradient of the n-type semiconductor

$$J_n \propto \frac{dn}{dx}$$

- (2) The equation for diffusion current density and concentration gradient of the p-type semiconductor

$$J_p \propto \frac{dp}{dx}$$

- Here  $J_n$  represents the density with respect to electrons and  $J_p$  represents the density with respect to holes.

### Diffusion Current Density Equation

- The diffusion density because of the carrier concentration of electrons is given by

$$J_n = +eD_n \frac{dn}{dx}$$

- Similarly, the diffusion density because of the carrier concentration of holes can be written as

$$J_p = -eD_p \frac{dp}{dx}$$

- Here  $D_n$  stands for the diffusion coefficient with respect to electrons and  $D_p$  stands for the diffusion coefficient with respect to holes.
- The above equation is for the densities of diffusion densities with respect to electrons and holes but the overall density of the current of respective holes or electrons can be given by the sum of the diffusion current and the drift current.
- The overall diffusion density with respect to electrons can be given as

$$J_n = \text{Drift current} + \text{diffusion current}$$

$$J_n = en\mu_n E + eD_n \frac{dn}{dx}$$

- The overall diffusion density with respect to holes can be given by the equations for the individual densities of electrons as well as holes. Therefore the overall current density can be given by

$$J_p = \text{Drift current} + \text{diffusion current}$$

$$J_p = ep\mu_p E + eD_p \frac{dp}{dx}$$

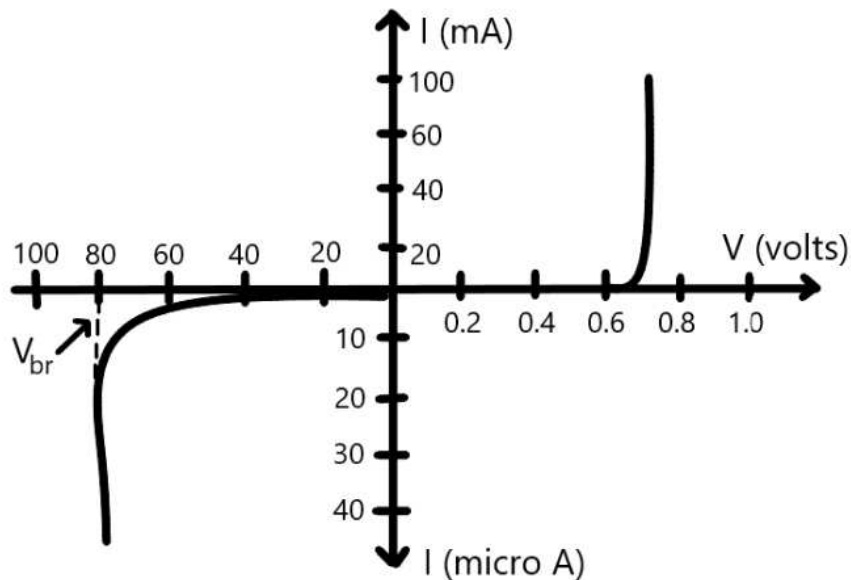
- In this way, the equations for the diffusion current densities are described for holes as well as electrons. The diffusion current in the semiconductor has occurred before the application of external supply. It is also termed as the process of recombination in order to achieve uniformity

- (c) (i) Draw characteristic curve for p-n junction diode.**  
**(ii) Discuss forward bias characteristics with proper circuit diagram.**  
**(iii) Discuss reverse bias characteristics with proper circuit diagram.**

**Ans :**

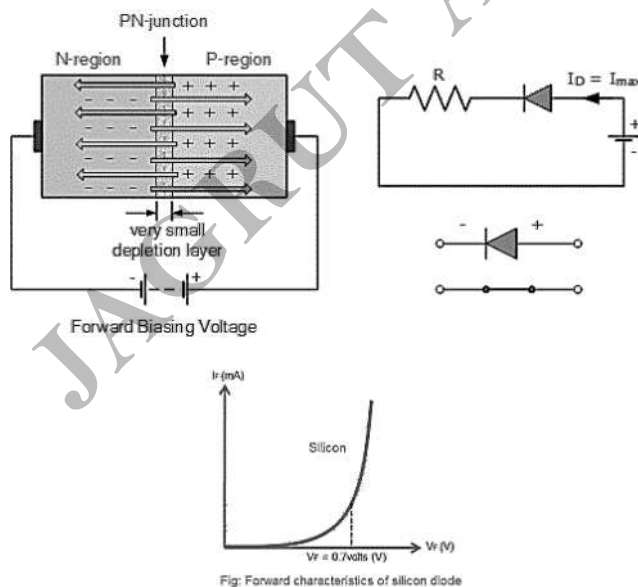
- (i) Draw characteristic curve for p-n junction diode.**

→



**(ii) Discuss forward bias characteristics with proper circuit diagram.**

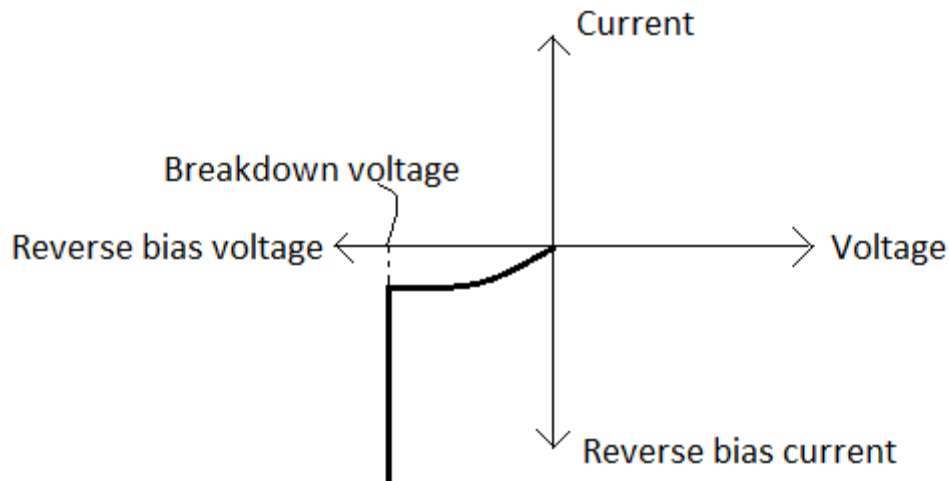
- The attached diagram shows the circuit of p-n junction under forward bias.
- In forward-bias, p-side is supplied with a positive potential and n-side is supplied with a negative potential. Hence, electric field generated is opposite that of the electric field generated by barrier potential. This leads to the generation of extra carriers on both sides and hence, reduction of depletion width and barrier potential.
- Hence, resistance of the diode becomes very small and it can be approximated to a short circuit after application of forward cutoff voltage.
- Corresponding V-I characteristics are shown in the attached figure.



**(iii) Discuss reverse bias characteristics with proper circuit diagram.**

- Reverse Bias Diode
- In reverse bias diodes, the p side of the pn junction is connected to the negative terminal of the battery used in the circuit, while the n-type is connected to the positive terminal. On applying voltage, the barrier width increases in reverse-biased semiconductor diodes. It can be understood in this way: the direction of electrical potential is similar to that of barrier potential, which means if the voltage is increased, it will sum up the barrier potential. Additionally, the motion of the charge carrier will also decrease because of the barrier. Hence, with increased reverse bias voltage, the current flow slows down; however, reverse current will

reach a higher value. It can be referred to as junction breakdown, and the reverse voltage is known as breakdown voltage at this point.



Reverse bias characteristics of P-N junction diode

→ Reverse Bias I-V Characteristics

→ When the reverse current flows, it is caused by the less amount of charge carrier. Therefore, the reverse current remains constant for a large part of the voltage applied across the terminals. At the breakdown voltage level, there is an exponential increase in the current. It can also cause overheating of the device.

**Q-3 (a) A potential barrier of 0.6 V exists across of p-n junction. The intensity of the electric field in this region is  $2.4 \times 10^6$  V/m. Find the width of depletion region.**

**Ans :**

→ Given:

$$V = 0.6V$$

$$E = 2.4 \times 10^6 \text{ V/m}$$

→ From equation,

$$E = \frac{V}{d}$$

$$\therefore d = \frac{V}{E} = \frac{0.6}{2.4 \times 10^6}$$

$$= 0.25 \times 10^{-6}$$

$$\therefore d = 2.5 \times 10^{-7} \text{ m}$$

**(b) (i) Mention any two applications of LED.**

**(ii) Calculate the value of band gap for a LED for the emission of blue light of wavelength 452 nm. ( $h = 6.63 \times 10^{-34}$  J s,  $c = 3 \times 10^8$  m/s)**

**Ans :**

(i) Applications of LED :

→ Picture phones and digital watches

→ Camera flashes and automotive heat lamps

→ Digital computers and calculators

→ Traffic signals and Burglar alarms systems

(ii) Calculate of the value of band gap for a LED

→ Given:

$$h = 6.63 \times 10^{-34} \text{ J s}$$

$$c = 3 \times 10^8 \text{ m/s}$$

$$\lambda = 452 \text{ nm}$$

→ Bond gap

$$\begin{aligned} E &= \frac{hc}{\lambda} \\ &= \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{452 \times 10^{-9}} \\ &= 0.0439 \times 10^{-17} \\ &= 4.39 \times 10^{19} \text{ J} \\ &= 2.74 \text{ eV} \end{aligned}$$

**(c) Derive formula of fermi energy level for n-type semiconductor.**

**Ans :**

→ The Set (group) of energy levels is known as the energy band. In the energy band diagram, there are mainly two energy bands. Those are the conduction band and valence band. The region between these two energy bands is known as the forbidden energy gap or energy gap in short.

→ Fermi level is an energy level, which lies in the energy band diagram. It distinguishes the set of levels that are occupied with electrons from the set of levels that are not occupied with electrons. We can define the Fermi level in two ways.

→ It is the minimum energy level, beyond which all the levels are not occupied with electrons (empty) at  $T=0\text{K}$ .

→ It is the maximum energy level, below which all the levels are filled with electrons at  $T=0\text{K}$ .

→ **Derivation for Fermi energy level ( $E_f$ ) in case of N-type semi-conducting material**

$N_D$  = Total number of Donor atoms

$N_D^+$  = Ionized donor impurity concentration

$N_D^0$  = Unionized donor atom present at ED.

$N_e$  = Total number of electrons (concentration) in C.B.

$N_h$  = Total number of holes (concentration) in V.B.

1. For conduction, the total number of electrons at C.B is due to

2. (a) intrinsic process (generation of hole at V.B. as well)

(b) extrinsic process (ionization of donor atoms)

Which can be expressed mathematically

$$N_e = N_h + N_D^+ \dots \dots (i)$$

3. At 0 K temperature, all the valence bands are completely filled and the transition of electron from V.B to C.B. cannot be expected (@  $T=0\text{K}$   $N_h=0$ ). So, equation (i) can be rewritten as...

$$N_e = N_D^+ \quad (i')$$

$$N_e = N_D^+ = N_D - N_D^0$$

$$N_D^+ = N_D [1 - f(E_D)] \dots \dots (ii)$$

$$\text{Ref: } f(E_D) = \frac{N_D^0}{N_D} = \frac{\text{unionized}}{\text{total}} = 1$$

4. We know,

$$\begin{aligned} f(E_D) &= \frac{1}{1 + e^{\frac{E_D - E_f}{k_B T}}} \\ f(E_D) &= \left[ 1 + e^{\left( \frac{E_D - E_f}{k_B T} \right)} \right]^{-1} \end{aligned}$$

$$[1 - f(E_D)] = 1 - \left[ 1 - e^{\left(\frac{E_D - E_F}{k_B T}\right)} \right]$$

$$[1 - f(E_D)] = e^{\left(\frac{E_D - E_F}{k_B T}\right)} \dots \dots \dots (iii)$$

5. Let us substitute values from equation (iii) to equation (ii),

$$N_D^+ = N_D [1 - f(E_D)]$$

$$N_D^+ = N_D \left[ e^{\left(\frac{E_D - E_F}{k_B T}\right)} \right] \dots \dots \dots (iv)$$

$$N_{extrinsic} = N_D^+ = N_D \left[ e^{\left(\frac{E_D - E_F}{k_B T}\right)} \right] \dots \dots \dots (iv)$$

6. Now, the expression for total number of electrons present at conduction band for both the cases, (i) intrinsic and extrinsic can be equated as...

$$N_i = N_e \dots \dots \dots (v)$$

$$N_{intrinsic} = n = N_c e^{-\left(\frac{E_c - E_f}{k_B T}\right)} \dots \dots \dots (vi)$$

7. From, equation (v) and (vi)...

$$N_c e^{-\left(\frac{E_c - E_f}{k_B T}\right)} = N_D \left[ e^{\left(\frac{E_D - E_f}{k_B T}\right)} \right]$$

$$\frac{N_D}{N_c} = e^{\left(\frac{E_f - E_c + E_f - E_D}{k_B T}\right)}$$

$$\ln \left[ \frac{N_D}{N_c} \right] = \frac{2E_f - (E_c + E_D)}{k_B T}$$

$$E_f = \frac{E_c + E_D}{2} + \frac{k_B T}{2} \ln \left[ \frac{N_D}{N_c} \right] \dots \dots \dots (vii)$$

8. Now @ Zero Kelvin temperature...equation (vii) can be written as,

$$E_f = \frac{E_c + E_D}{2} \quad (FINAL) \dots \dots \dots (vii)$$

#### Q-4 (a) (i) What is called optoelectronic device?

(ii) Name the types of metal-semiconductor junction.

(iii) What is called exciton?

Ans :

(i) An optoelectronic device is a device that can source, detect, and control light. It uses the principles of electronics and optics to convert electrical signals into optical signals (and vice versa).

(ii) The types of metal-semiconductor junctions are:

1. Schottky Diode:

→ Formed between a metal and a semiconductor, typically silicon or gallium arsenide (GaAs). It has a low forward voltage drop and fast switching speed.

2. Ohmic Contact:

→ A low-resistance junction between a metal and a semiconductor, used to provide a low-resistance electrical connection.

(iii) An exciton is a bound state of an electron and an electron hole which are attracted to each other by the electrostatic Coulomb force. It is a quasiparticle that exists in insulators, semiconductors, and some liquids. Excitons can exist in two forms:

1. Bound Exciton:

→ The electron and hole are tightly bound together, behaving as a single particle with an energy less than the energy of a free electron and hole pair.

2. Free Exciton:

→ The electron and hole are less tightly bound and can move independently, similar to an electron-hole pair in a semiconductor.

**(b) Discuss Frenkel and Wannier-Mott exciton in brief.**

**Ans :**

**1. Frenkel Exciton:**

- Frenkel excitons are a type of exciton that occurs in molecular crystals or organic semiconductors where the electron and hole are localized on the same molecule or atom. This localization arises due to the strong electron-phonon coupling in these materials, which leads to the formation of a bound electron-hole pair within a single molecule or atom. The small size of Frenkel excitons makes them strongly interact with lattice vibrations (phonons), leading to phenomena such as vibronic coupling and the formation of polarons.
- One of the key characteristics of Frenkel excitons is their high binding energy, which can be several electron volts in organic materials. This high binding energy is a result of the strong Coulomb interaction between the electron and hole within the same molecule or atom. The small size and high binding energy of Frenkel excitons make them important in the optical and electronic properties of molecular crystals and organic semiconductors. For example, Frenkel excitons are responsible for the absorption and emission of light in these materials, giving rise to their characteristic optical spectra.

**2. Wannier-Mott Exciton:**

- Wannier-Mott excitons are a type of exciton that occurs in inorganic semiconductors or insulators where the electron and hole are spatially separated, with the electron localized on one atom or molecule and the hole localized on another. This spatial separation arises due to the strong Coulomb interaction between the electron and hole, which causes them to be delocalized over several lattice sites. Unlike Frenkel excitons, which are localized within a single molecule or atom, Wannier-Mott excitons are delocalized over a larger region of the crystal lattice.
- One of the key characteristics of Wannier-Mott excitons is their large size, which can be on the order of the lattice constant of the crystal. This large size results in a weak interaction with lattice vibrations (phonons), leading to a longer exciton lifetime compared to Frenkel excitons. Wannier-Mott excitons are also characterized by their high mobility, which allows them to diffuse through the crystal lattice and interact with defects or impurities. These properties make
- Wannier-Mott excitons important in the transport and recombination of charge carriers in inorganic semiconductors and insulators.

**(c) What is photovoltaic effect? Explain construction and working of solar cell in detail.**

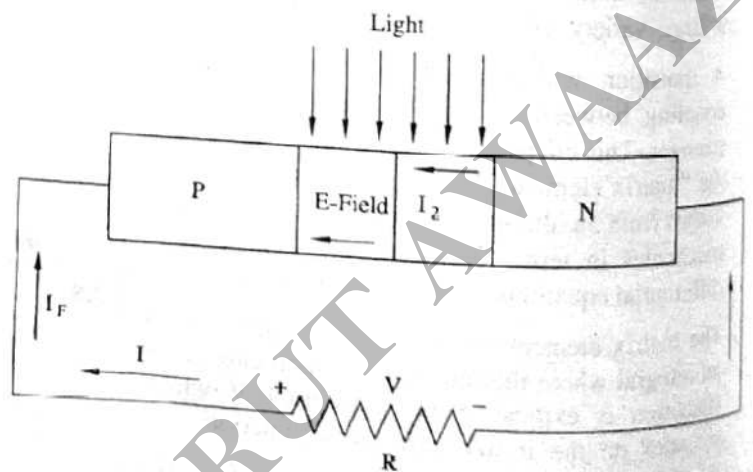
**Ans :**

**PHOTOVOLTAIC EFFECT:-**

- In photoelectric effect when radiation is incident on a metal surface electrons are ejected. In photovoltaic effect, certain materials being exposed to radiation generate electron-hole pairs available for conduction. As a result a voltage is developed across the material. The radiation energy  $E = h\nu$  is required to be greater than the band gap energy  $E_g$  of the material. This is a phenomenon in which light energy is converted into electrical energy.

### SOLAR CELL :

- Solar cell is a semiconductor device that converts solar energy into electrical energy. This is a p-n junction diode with very doping level. Solar cells have a flat shape with a very thin top layer. So that the incident solar energy can reach the junction area.
- As the solar radiation is incident on the device due to the radiation energy  $E = h\nu \geq E_g$  electron-hole pairs are generated in p and n region.
- In the energy band structure of the solar cell in fig it is seen that the conduction band is lower in the region than that in the p region. Hence, the generated electrons of the conduction band of p region travel to the conduction band of n region which is at a lower electron energy level. Similarly the holes created in the valence band of the n region move to the valence band of the p region at a lower hole energy level.



- This diffusion of electrons and holes through the junction constitutes the current.
- The top surface of the solar cell is coated with an antireflection film to maximize the utilization of the incident solar energy by the junction.
- A solar cell does not need a power supply. It generates power.
- Materials used for solar cell are different types of semiconductor, single crystal, polycrystal, thin silicon wafers etc.

### Q-4 (a) (i) What is Hall effect?

(ii) The Hall coefficient of a semiconducting material is  $2.4 \times 10^{-4} \text{ m}^3/\text{C}$ . Calculate the mobility and carrier concentration of the carrier if resistivity is  $6 \times 10^{-3} \Omega \text{ m}$ .

Ans :

**(i) Hall Effect:** The Hall effect is the production of a voltage difference (the Hall voltage) across an electrical conductor, transverse to an electric current in the conductor and to an applied magnetic field perpendicular to the current. This phenomenon is due to the Lorentz force acting on the moving charges (electrons or holes) in the presence of the magnetic field, which causes the charge carriers to accumulate on one side of the conductor, creating a measurable voltage difference.

(ii) Calculation:



→ The Hall coefficient ( $R_H$ ) is related to the carrier concentration ( $n$ ), charge ( $q$ ), and mobility ( $\mu$ ) of the charge carriers by the formula:

$$R_H = \frac{1}{nq}$$

where:

$R_H$  = Hall coefficient

$n$  = carrier concentration

$q$  = charge of the carrier ( $1.6 \times 10^{-19}$  C for electrons)

$\mu$  = mobility

→ Given:

$$R_H = 2.4 \times 10^{-4} \text{ m}^3/\text{C}$$

$$\text{resistivity } (\rho) = 6 \times 10^{-3} \Omega \text{ m}$$

→ The resistivity ( $\rho$ ) is related to the mobility ( $\mu$ ), charge ( $q$ ), and carrier concentration ( $n$ ) by the formula:

$$\rho = \frac{1}{nq\mu}$$

→ We can rearrange this formula to solve for  $n$ :

$$n = \frac{1}{R_H q}$$

→ Substituting the values:

$$n = \frac{1}{2.4 \times 10^{-4} \times 1.6 \times 10^{-19}}$$

$$n = \frac{1}{3.84 \times 10^{-23}}$$

$$n = 2.604 \times 10^{22} \text{ m}^{-3}$$

→ Now, to find the mobility ( $\mu$ ), we can use the formula:

$$\mu = \frac{1}{\rho n q}$$

→ Substitute the values:

$$\mu = \frac{1}{6 \times 10^{-3} \times 2.604 \times 10^{22} \times 1.6 \times 10^{-19}}$$

$$\mu = \frac{1}{2.48448 \times 10^{-2}}$$

$$\mu = 40.22 \text{ m}^2/\text{V} \cdot \text{s}$$

→ Therefore, the carrier concentration is  $2.604 \times 10^{22} \text{ m}^{-3}$  and the mobility is  $40.22 \text{ m}^2/\text{V} \cdot \text{s}$ .

### (b) Discuss Fermi's golden rule for transition probability.

Ans :

→ In quantum physics, Fermi's golden rule is used to calculate transition rates. The transition rate depends upon the strength of coupling between the initial and final state of a system and upon the number of ways the transition can happen (joint density of states).

→ The transition probability is given by:

$$\lambda_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 Z_f$$

- Where,  $\lambda_{if}$  is transition probability,  $|M_{if}|^2$  is matrix element for interaction and  $Z_f$  is joint density of final state.
- The above equation is known as fermi's golden rule.
- The transition probability  $\lambda$  is called the decay probability and is related to mean lifetime  $\tau$  of the state.

$$\lambda = \frac{1}{\tau}$$

- The general form of fermi's golden rule can be applied to atomic transitions. Nuclear decay and scattering.
- This coupling term is traditionally called the matrix element for the transition.
- This matrix element can be placed in the form of an integral, where the interaction (that causes transition) is expressed as a potential  $v$  that operates on initial state wave function.
- The transition probability is proportional to the square of integral of interaction over all of the space appropriate to the problem.

$$M_{if} = \int \psi_f^* \cdot V \cdot \psi_i \cdot dv$$

- Where,  $V$  is operator for physical interaction that couples initial and final states,  $\psi_f^*$  is wave function for final state and  $\psi_i$  is wave function for initial state.

**(c) Discuss in detail UV-VIS method for band gap measurement of semiconductor.**

**Ans :**

- UV- Vis Spectroscopy is related to the interaction of light with matter.
- As light is absorbed by matter, the result is an increase in the energy content of the atoms or molecules.
- This method is used to measure the energy band gap of different materials, by measuring absorption spectrum.
- Bandgap refers to the energy difference between bottom of conduction band and top of valence band, through which electrons are able to jump from one band to another.
- The instrument used in UV-Vis spectroscopy is called UV-Vis spectro-photometer.
- It measure the intensity of light after passing through a sample (1), and compares it to the intensity of light before it passes through the sample (10).
- A light of wavelength ( $\lambda$ ) and energy ( $h\nu$ ) is made to pass through monochromator to get a parallel beam.
- It then passes through a beam splitter and is incident on two cells, a reference cell and a sample cell.
- The intensities of light from reference and sample cells is collected by the detector.
- The ration of intensities is called transmittance (T).

$$i.e T = \frac{I}{I_0}$$

- The transmittance (T) is usually expressed in percentage (%T).
- If we plot %T w.r.t. to concentration of sample, we get an exponential decrease in transmittance, with an increase in concentration.
- Higher the concentration, more is the absorption so less is the value of I, through the sample cell.

→ As it is difficult to extract characteristics from the exponential relation, we define a relation absorption (A)

$$\text{Absorption (A)} = \log \left( \frac{I_0}{I} \right)$$

→ The Tauc's relation is used to determine the bandgap in semiconductor.

$$\alpha h\nu = A(h\nu - E_g)^n$$

Where,

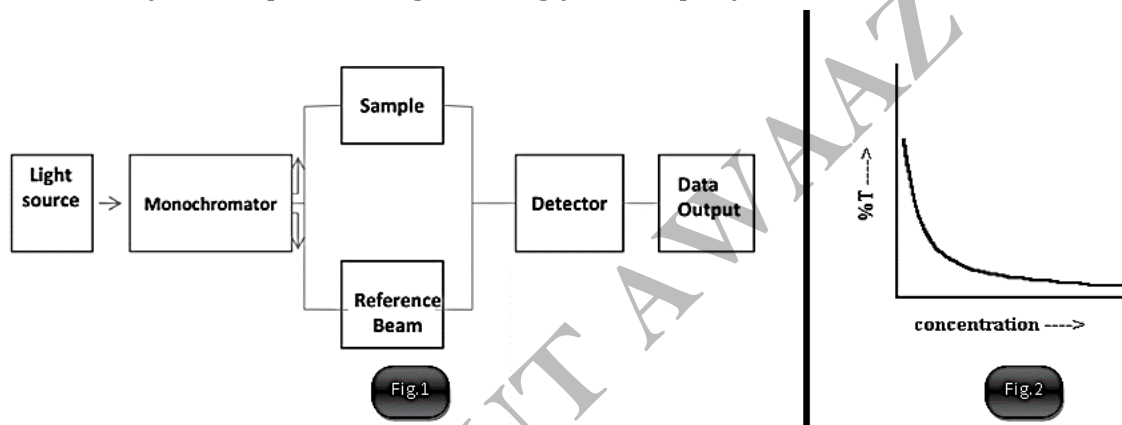
$$\alpha = \text{absorption coefficient} = \frac{\ln(\frac{1}{T})}{x}$$

$$T = \text{transmittance} = \frac{1}{I_0}$$

$x$  = Thickness of the sample

$n = 2, \frac{1}{2}, \frac{2}{3}$  and  $\frac{1}{3}$  for direct allowed, indirect allowed, direct forbidden and indirect forbidden transitions respectively.

→ Now, we can plot a graph of  $(\alpha h\nu)^{\frac{1}{n}}$  along x - axis vs  $h\nu$  (along y - axis), we will get slop as  $A^{\frac{1}{n}}$  and y intercept as  $A^{\frac{1}{n}}$  Eg. Dividing y intercept by  $A^{\frac{1}{n}}$  we can estimate the band gap.



**Q-5 (a) Calculate the critical current through a long thin superconducting wire of radius  $10^{-3}$  m. The critical magnetic field is  $6.2 \times 10^3$  A/m.**

**Ans :**

→ Given :

$$r = 10^{-3} \text{ m}$$

$$H_c = 6.2 \times 10^3 \text{ A/m}$$

→ Now, Critical Current

$$I_c = 2\pi r H_c$$

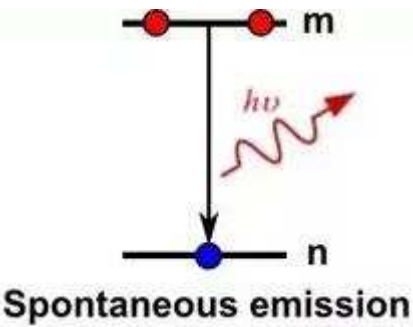
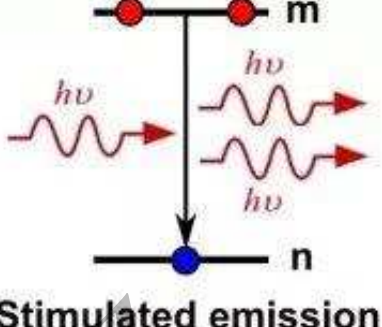
$$= 2 \times 3.14 \times 10^{-3} \times 6.2 \times 10^3$$

$$I_c = 38.936 \text{ A}$$

**(b) State any four points of differences between spontaneous and stimulated emission.**

**Ans :**

Sr. No.	Spontaneous emission	Stimulated emission
1.	The transition of an electron from the excited state to the ground state happens as a result of the natural tendency of the electron without the action of any external agent. The radiation produced as a result of such transitions is called as spontaneous radiation.	Stimulated emission of radiation is the process whereby photons are used to generate other photons that have exact phase and wavelength as that of parent photon.

2.	This phenomenon is found in LEDs, Fluorescent tubes.	This phenomenon is found in LEDs, Fluorescent tubes.
3.	This phenomenon is found in LEDs, Fluorescent tubes.	Population inversion is achieved by various 'pumping' techniques to get amplification giving the LASER its name "Light amplification by stimulated emission of radiation."
4.	No external stimuli required.	Thus stimulated emission is caused by external stimuli.
5.	 <p>Spontaneous emission</p>	 <p>Stimulated emission</p>

**(c) Discuss in detail experimental procedure for DLTS.**

**Ans :**

→ Deep Level Transient Spectroscopy (DLTS) is a powerful technique used to study the energy levels of deep traps in semiconductors. These traps can significantly affect the electrical properties of semiconductor devices. Here's a detailed description of the experimental procedure for DLTS:

1. **Sample Preparation:** Start by preparing the semiconductor sample. This typically involves cleaning the sample to remove any surface contaminants and ensuring a high-quality surface for measurements.
2. **Doping:** If the sample is not already doped, it may be doped to introduce impurities and create the desired electronic properties.
3. **Contacts:** Create electrical contacts on the sample. These contacts are used to apply a voltage to the sample and measure the resulting currents.
4. **Mounting:** Mount the sample in a DLTS setup. The sample is typically placed in a cryostat to control the temperature during measurements.
5. **Temperature Control:** Cool the sample to a low temperature, typically around liquid helium temperatures (4 K). The low temperature helps to reduce thermal noise and stabilize the deep traps.
6. **Biasing:** Apply a reverse bias to the sample. This bias creates an electric field across the depletion region of the semiconductor, allowing deep traps to be filled or emptied.
7. **Pulse Sequence:** Apply a series of voltage pulses to the sample. These pulses are used to fill or empty the deep traps, depending on their energy levels.

8. **Current Measurement:** Measure the current flowing through the sample during the pulse sequence. This current is proportional to the number of traps that are filled or emptied.
9. **Analysis:** Analyze the current measurements to determine the energy levels of the deep traps. This analysis involves fitting the current data to a model that describes the behavior of the traps.
10. **Repeat:** Repeat the measurements at different temperatures or with different pulse sequences to obtain a more detailed understanding of the deep traps in the sample.
11. **Data Interpretation:** Interpret the data to extract information about the deep traps, such as their energy levels, capture cross-sections, and concentrations.
12. **Comparison:** Compare the results with theoretical models or with data from other techniques to validate the findings.

→ DLTS is a complex technique that requires careful sample preparation and precise measurements. However, it provides valuable information about the deep traps in semiconductors, which is essential for understanding and improving the performance of semiconductor devices.

**Q-5 (a) The critical temperature of a superconductor is 7.5 K. Calculate the critical field at 5 K. At 0 K the critical field is 0.24 T.**

**Ans :**

→ Given :-

$$H_0 = 0.24 \text{ T}$$

$$T_c = 7.5 \text{ K}$$

$$T = 5 \text{ K}$$

→ From equations ,

$$\begin{aligned}
 H_c &= H_0 \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right] \\
 &= 0.24 \left[ 1 - \left( \frac{5}{7.5} \right)^2 \right] \\
 &= 0.24 [1 - (0.667)^2] \\
 &= 0.24 [0.555] \\
 &= 0.133 \text{ T}
 \end{aligned}$$

**(b) Write a short note on London penetration depth.**

**Ans :**

- Maxwell's equations could not explain the zero resistance and perfect diamagnetism observed as main characteristics of superconductivity.
- F. London and H. London (London brothers) suggested that motion of superconducting electrons in the presence of applied electric field E.
- If a magnetic field is applied to a superconductor which is initially in zero field, the magnetic field is a function of time.
- The potential decay of magnetic field at the interior surface of superconductor.
- Mathematical expression for the Hall voltage is given by:

$$B(x) = B_0 e^{-\left(\frac{x}{\lambda}\right)}$$

Where  $B_0$  = magnetic field at the surface

$x$  = distance inside the superconductor from surface

$\lambda_L$  = Penetration depth

→ The potential decay of magnetic field at the interior surface of superconductor.

→  $\lambda_L$  is the distance across which the magnetic field becomes 'e' times weaker.

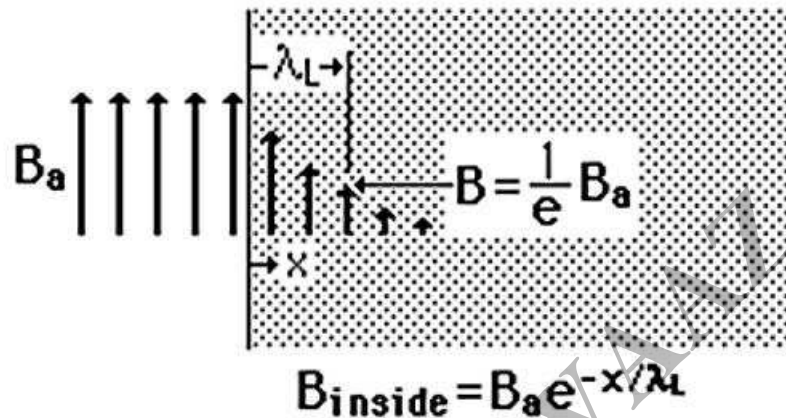
→  $\lambda_L$  can be formulated as:

$$\lambda_L = \frac{\sqrt{m}}{\mu_0 n q^2}$$

Where ,  $m$  = charge carrier of mass

$n$  = number of density

$\mu_0$  = absolute permeability



(c) (i) Discuss BCS theory of superconductivity in brief.

(ii) Draw constructive diagram of SQUID and mention its application.

Ans :

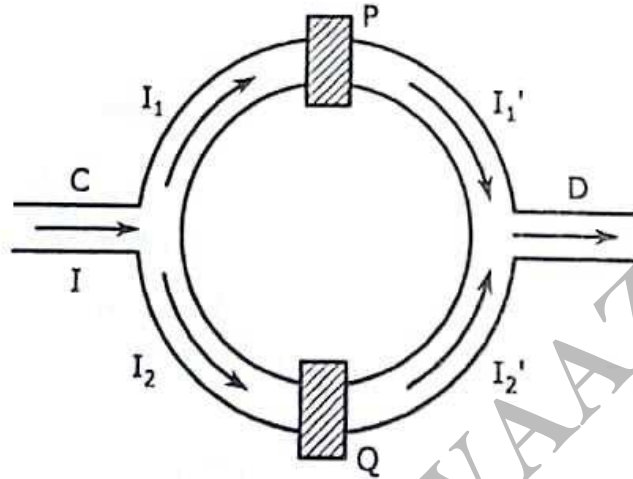
(i) BCS theory of superconductivity

→ The BCS theory of superconductivity, developed by John Bardeen, Leon Cooper, and Robert Schrieffer in 1957, explains how superconductivity occurs in certain materials at low temperatures. Here's a brief overview of the key concepts:

1. **Cooper Pairs:** BCS theory proposes that at low temperatures, electrons in a superconductor form pairs known as Cooper pairs. These pairs are formed due to the attractive interaction between electrons mediated by lattice vibrations (phonons) in the crystal lattice.
2. **Zero Resistance:** Cooper pairs move through the crystal lattice without scattering off defects or impurities, leading to zero electrical resistance. This phenomenon is one of the defining characteristics of superconductivity.
3. **Energy Gap:** The formation of Cooper pairs results in the opening of an energy gap in the electronic band structure of the superconductor. This energy gap represents the minimum energy required to break a Cooper pair and is responsible for the absence of resistance.
4. **Macroscopic Quantum State:** Superconductors exhibit macroscopic quantum behavior, where the wave functions of Cooper pairs overlap, leading to quantum effects on a macroscopic scale.

5. **Meissner Effect:** Superconductors expel magnetic fields from their interior, a phenomenon known as the Meissner effect. This expulsion of magnetic flux is a consequence of the perfect diamagnetism exhibited by superconductors.
6. **Critical Temperature:** Each superconductor has a critical temperature ( $T_c$ ) below which it becomes superconducting. Above this temperature, the material behaves like a normal conductor.

(ii) Constructive diagram of SQUID and its application.



→ Applications:

### 1. Magnetic Field Sensing:

SQUIDS are extremely sensitive to magnetic fields and are used in devices such as magnetometers to measure very small magnetic fields. They can detect magnetic fields as weak as a few femtoteslas, making them invaluable for a wide range of applications, including medical imaging (MRI), geophysical exploration, and materials testing.

### 2. Quantum Computing:

SQUIDS are also used in quantum computing research. They can be used to create qubits, the basic units of quantum information, by exploiting the quantum properties of superconductors and Josephson junctions.

### 3. Gravitational Wave Detection:

In some configurations, SQUIDS can be used as extremely sensitive detectors of gravitational waves. By measuring the tiny changes in magnetic fields induced by passing gravitational waves, SQUIDS can contribute to our understanding of the universe's most energetic events.

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