As Per The New Revised Syllabus of
Gujarat Technological University
w.e.f. Academic Year 2018-2019

PHYSICS

(GROUP-II)

Semester - I - II

- Dr. D. M. Patel

With Solved
University
Question Papers
upto
May 2019

- Bio Medical / Computer / Electrical & Electronics
- Electronics & Communication
- Information Technology
- Instrumentation & Control Engineering
- Information & Communication Technology
- Computer Science and Engineering
- Power Electronics

ATUL PRAKASHAN
GANDHI ROAD, AHMEDABAD

GUJARAT TECHNOLOGICAL UNIVERSITY

Subject Name : Physics (Group-II)

Subject Code : 3110018

Teaching and Examination Scheme :

Teaching Scheme			Credits	Examination Marks				Total Marks
				Theory Marks		Practical Marks		
L	T	P	C	ESE (E)	PA (M)	ESE (V)	PA (I)	
3	0	2	4	70	30	30	20	150

Content :

Sr. No.	Topics	Total Hrs.	Module Weightage
1.	**ELECTRONIC MATERIALS** • Free electron theory. • Density of states and energy band diagrams. • Kronig-Penny model (to introduce origin of band gap), Energy bands in solids. • E-k diagram, Direct and indirect bandgaps. • Types of electronic materials : Metals, semiconductors and insulators. • Density of states, Occupation probability. • Fermi level, Effective mass, Phonons.	8	22
2.	**SEMICONDUCTORS** • Intrinsic and extrinsic semiconductors. • Dependence of Fermi level on carrier-concentration and temperature (equilibrium carrier statistics) • Carrier generation and recombination, Carrier transport : diffusion and drift, p-n junction. • Metal-semiconductor junction (Ohmic and Schottky), Semiconductor materials of interest for optoelectronic devices.	10	27
3.	**LIGHT-SEMICONDUCTOR INTERACTION** • Optical transitions in bulk semiconductors : absorption, spontaneous emission, and stimulated emission. • Joint density of states. • Density of states for photons. • Transition rates (Fermi's golden rule) • Optical loss and gain; Photovoltaic effect, Exciton. • Drude model.	6	17

4.	**MEASUREMENTS** • Four-point probe and Van Der Pauw measurements for carrier density. • Resistivity and hall mobility. • Hot-point probe measurement, capacitance-voltage measurements. • Parameter extraction from I-V characteristics, DLTS. • Band gap by UV-V is spectroscopy, absorption/transmission.	6	17
5.	**SUPERCONDUCTIVITY** • Introduction of Superconductivity. • Properties of Superconductivity. – Effect of magnetic field – Meissner effect – Pressure effect – Impurity effect – Isotopic mass effect • Mechanism of Superconductivity : BCS Theory. • Penetration depth : Magnetic field. • Josephson's junction and its application • Application of Superconductors.	6	17

Index ...

1. ELECTRONIC MATERIALS .... 1 – 22

■ ❈ ■

CHAPTER

1

Electronic Materials

Contents

1.1 INTRODUCTION :

- We all know about two kind of materials in nature. i.e. conductors (Copper, Aluminium etc.) and Insulators (Wood, Plastic etc.)
- Certain materials are neither good conductors nor insulators, their conductivity lies between conductors and insulators.
- These types of materials are known as semiconductors (i.e. Silicon, Germanium etc.)
- Almost all electronic devices (i.e. diode, transistor etc.) are made up of semiconductors.
- Therefore, to study their characteristics and behaviour, we should be familiar with the basic physics of semiconductors in details.

1.2 ATOM AND ITS STRUCTURE :

- All the materials are composed of very small particles called atoms.
- Atoms are made of 3 type of particles,

1. Electron
2. Protons
3. Neutrons

- According to Bohr's model, an atom has a central core called the nucleus, which contain proton and neutrons.
- Electrons revolve around the nucleus in different orbits.
- We know that, the electrons are negatively charged (–), while the protons are positively charged (+) and the neutrons have no charge.
- In the normal atom, the number of protons equals the number of electrons. Thus an atom is electrically neutral.
- The basic structure of an atom is shown symbolically in Fig. 1.1.

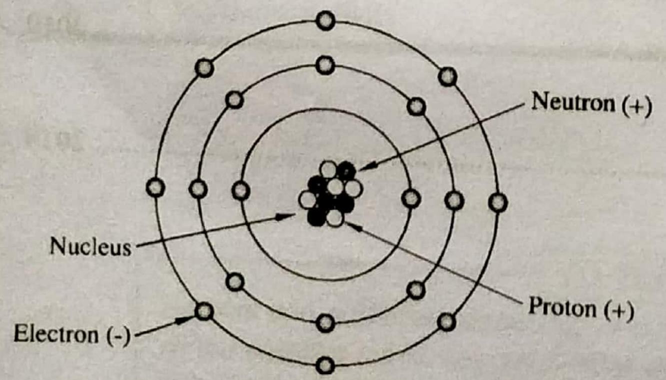


FIG. 1.1 : ATOM AND ITS STRUCTURE

1. **Electron :**

- Electrons are negatively charged particles which are moving with high velocity around the nucleus of atom in specific paths called orbits.
- The mass of the electron is very small, its mass is 9.107 × 10^{-31} kilogram.
- Electrons are revolving around the nucleus in different orbits. Each orbit has certain fixed amount of energy.
- The mass of the electron is 1830 times smaller than the mass of proton.
- Therefore, the mass of the electron orbiting the nucleus is negligible compared to mass of protons and neutrons in the nucleus of a atom.
- Electron is denoted by a symbol 'e^-'.
- It has a charge of 1.602 × 10^{-19} Coulombs (C).

2. **Proton :**

- Proton is a positively charged particle.
- It is more heavier than electron, mass of proton is 1.672 × 10^{-27} kilograms.
- Proton is denoted by a symbol 'P^+'.
- It has a charge of 1.602 × 10^{-19} Coulombs (C).
- The charge of proton is equal to charge of electron but have opposite polarity.

3. **Neutron :**

- Neutron has no electric charge.
- The mass of neutron is slightly higher than that of the proton.
- Mass of neutron is 1.975 × 10^{-27} Kilograms.

1.3 ORBIT LEVELS OF ELECTRONS IN AN ATOM :

- The electrons are revolving around the nucleus in different orbits at a fixed distance from the nucleus. Each orbit or shell contains a fixed number of electrons.
- Generally, each orbit or shell contains a maximum of $2n^2$ electrons where, n is the number of shell. By just substituting the shell number in 'n' we can easily calculate number of electrons in each shell.
- First shell occupy a maximum of two electrons i.e., $(2 \times 1^2 = 2)$.
- Second shell occupy a maximum of eight electrons i.e., $(2 \times 2^2 = 8)$.

- Third shell occupy a maximum of 18 electrons i.e., $(2 \times 3^2 = 18)$ and so on.

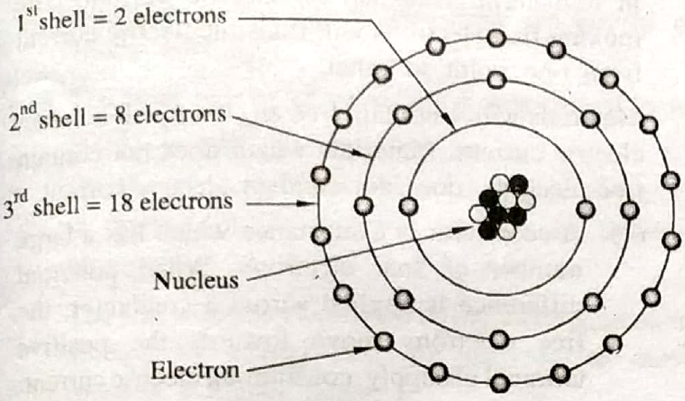


FIG. 1.2 : ORBIT LEVELS OF ELECTRONS IN A ATOM

- The electrons revolving around the nucleus in the first shell which is closest to the nucleus is strongly attached to the nuclease of strong attractive force. Electrons in first shell have least energy associated with it.
- The electrons revolving around the nucleus in the last shell which is farther away from the nucleus is loosely attached to the nucleus. The electrons in the outermost orbit or shell has highest energy.

1.4 VALENCE ELECTRONS :

- The electrons present in the outermost shell or orbit of an atom is called as valence electrons.

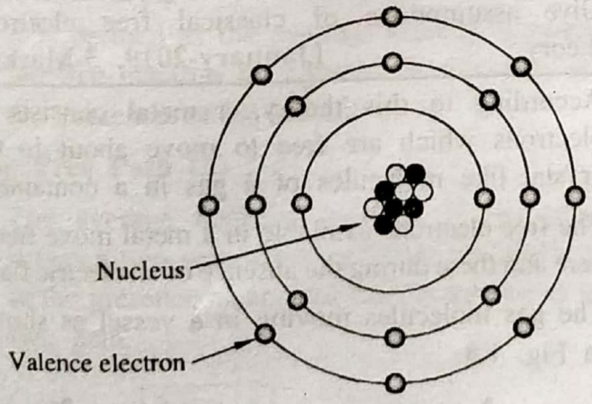
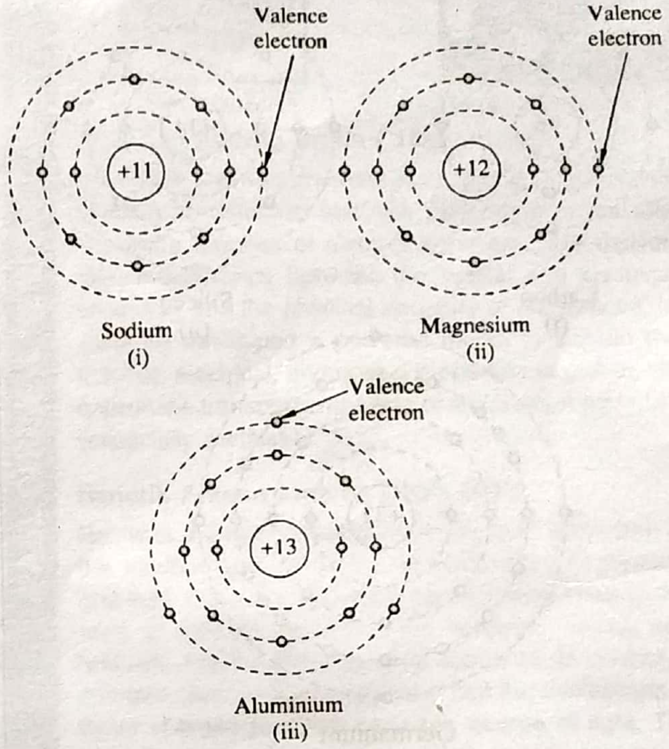


FIG. 1.3 : VALANCE ELECTRONS

- These electrons determine the electrical and physical properties of a material. The electrons revolving in the outer most orbit of a atom has highest energy level.
- Valence electrons are loosely attached to the nucleus. Therefore, less amount of energy is required to pull an electron from the outer most orbit.

(1) When the number of valence electrons of an atom is less than 4, the materials is usually known as a metal.

Examples are sodium, magnesium and aluminium which have 1, 2 and 3 valence electrons respectively (see Fig. 1.4).



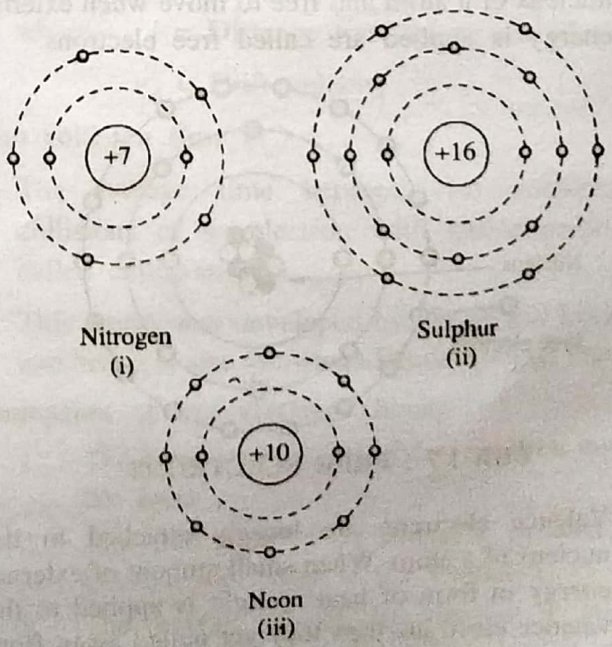
Sodium
(i)

Magnesium
(ii)

Aluminium
(iii)

FIG. 1.4

(2) When the number of valence electrons of an atom is more than 4, the material is usually known as an insulator. Examples are nitrogen, sulphur and neon (see Fig. 1.5).



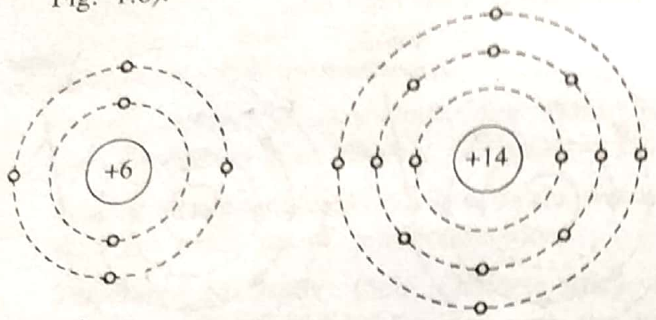
Nitrogen
(i)

Sulphur
(ii)

Neon
(iii)

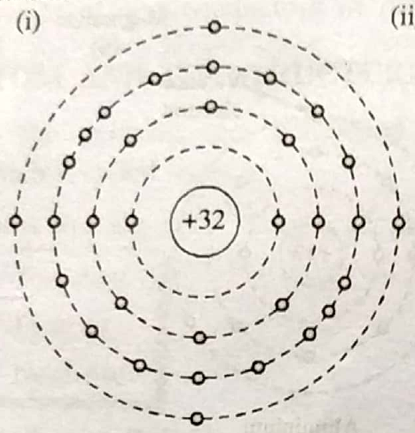
FIG. 1.5

(3) When the number of valence electrons of an atom is 4, the material has both metal and insulator properties and usually known as a semiconductor. Examples are carbon, silicon and germanium, (see Fig. 1.6).



Carbon
(i)

Silicon
(ii)



Germanium
(iii)

FIG. 1.6

1.5 FREE ELECTRONS :

- The electrons which are not attached to the nucleus of a atom and free to move when external energy is applied are called free electrons.

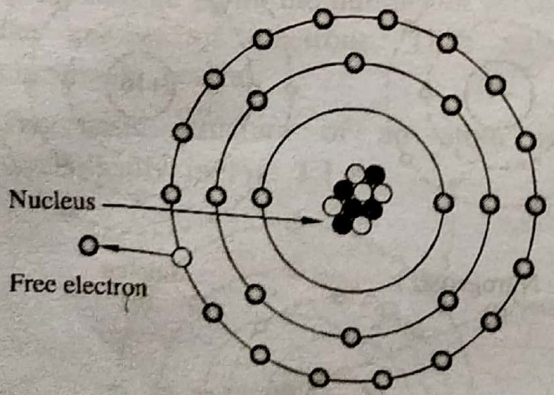


FIG. 1.7 : FREE ELECTRONS

- Valence electrons are loosely attached to the nucleus of a atom. When small amount of external energy in form of heat or light is applied to the valence electrons then they get pulled away from the parent atom and becomes free.
- The force of attraction of the nucleus does not act on the free electron. The flow of free electrons in a material is called an electric current. The moving free electrons will transmit electric current from one point to other.
- Materials which contain free electrons will conduct electric current. Materials which does not contain free electrons does not conduct electric current.

(1) A conductor is a substance which has a large number of free electrons. When potential difference is applied across a conductor, the free electrons move towards the positive terminal of supply, constituting electric current.

(2) An insulator is substance which has practically no free electrons at ordinary temperature. Therefore, an insulator does not conduct current under the influence of potential difference.

(3) A semiconductor is a substance which has very few free electrons at room temperature Consequently, under the influence of potential difference, a semiconductor practically conduct no current.

Syllabus Topic : Free Electron Theory

1.6 FREE ELECTRON THEORY :

GTU, January 2019

GTU Questions

1. Give assumptions of classical free electron theory. **[January-2019, 3-Marks]**

- According to this theory, a metal consists of electrons which are free to move about in the crystal like molecules of a gas in a container.
- The free electrons available in a metal move freely here and there during the absence of an electric field.
- The gas molecules moving in a vessel as shown in Fig. 1.8.

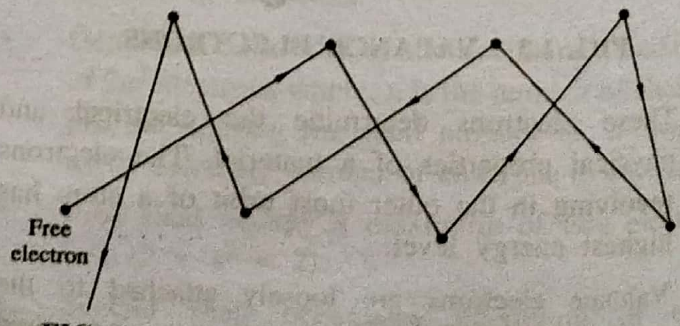


FIG. 1.8 : ABSENCE OF THE ELECTRIC FIELD – FREE ELECTRON

- These free electrons collide with other free electrons or positive ion cores or the walls of the container. Collisions of this type are known as elastic collisions.
- The total energy of an electron is assumed to be purely Kinetic Energy (KE).
- On the other hand, suppose an electric field (E) is applied to the material through an external arrangement as shown in Fig. 1.9.
- The free electrons available in the metal gain some amount of energy and are directed to move towards a higher potential.
- These electrons acquire a constant velocity known as drift velocity v_d.

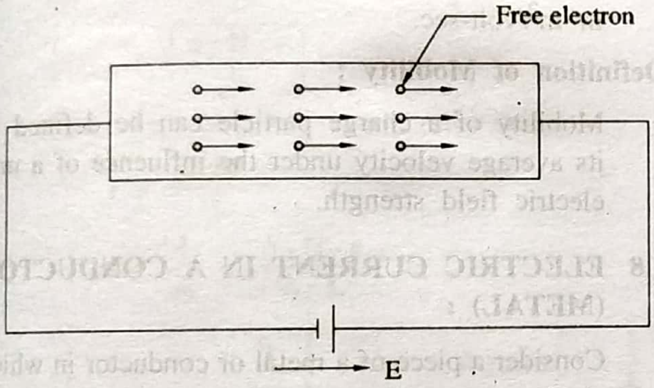


FIG. 1.9 : PRESENCE OF THE ELECTRIC FIELD – FREE ELECTRON

Drift Velocity v_d :

- It is defined as the average velocity acquired by the free electron in a particular direction during the presence of an electric field.

Mean Free Path (λ) :

- The average distance traveled by an electron between two successive collisions insdide a metal in the presence of applied field is known as mean free path.

$$\boxed{\lambda = v \cdot \tau}$$

where, λ = mean free path

v = Total velocity of an electron

Relaxation Time (τ) :

- The time taken by the free electron to reach equilibrium positin from its disturbed position in the presence of an electric field is called relaxation time.

PAUL DRUDE & HENDRIK LORENTZ


Paul Drude


Hendrik Lorentz

Paul Karl Ludwig Drude (1863 – 1906)

He was a German physicist specializing in optics. He wrote a fundamental textbook integrating optics with Maxwell's theories of electromagnetism. He derived the relationships between the optical and electrical constants and the physical structure of substances. In 1900 he developed a powerful model to explain the thermal, electrical, and optical properties of matter. He explain the transport properties of electrons in materials (especially metals).

Hendrik Antoon Lorentz (1853–1928)

He was a Dutch physicist. Lorentz was interested in the electromagnetic theory of electricity, magnetism, and light. His most important contributions were in the area of electromagnetism, the electron theory, and relativity. Lorentz theorized that atoms might consist of charged particles and suggested that the oscillations of these charged particles were the source of light. The experimental and theoretical work was honored with the Nobel prize in physics in 1902.

$$\boxed{\text{Relaxation Time, } \tau = \frac{l}{v_d}}$$

where, l = Distance traveled by the electron

v_d = Drift velocity

Mean collision time (τ_c) :

- The average time between two consecutive collisions of an electron with lattice points is called collision time.
- This theory was developed by Drude and Lorentz and hence is also known as Drude-Lorentz theory.

Assumption of free electron theory :

1. There exist a large no of free electron inside the metal.
2. The free electron situation is equated to gaseous molecules in the container.
3. The energy of an electron at a given temperature is $t = \frac{3}{2}$ KT.

4. The force of attraction or repulsion betweeen like charge and unlike charge is ignored.
5. The field due to positive ionic core is considered to be smaller hence neglected.
6. The electrical conductivity in a metal is a consequence of drift velocity in presence of applied electric field.

1.7 MOBILITY (μ) :

- Consider a conductor which is subjected to an electric field of strength E as shown in Fig. 1.10.
- Consider that n is the concentration of the free electrons; m, the mass and q, is the electric charge of the electron in the conductor.
- According to Newtons' second law of motion, the force F acquired by the electrons is equal to the force exerted by the field on the electrons.

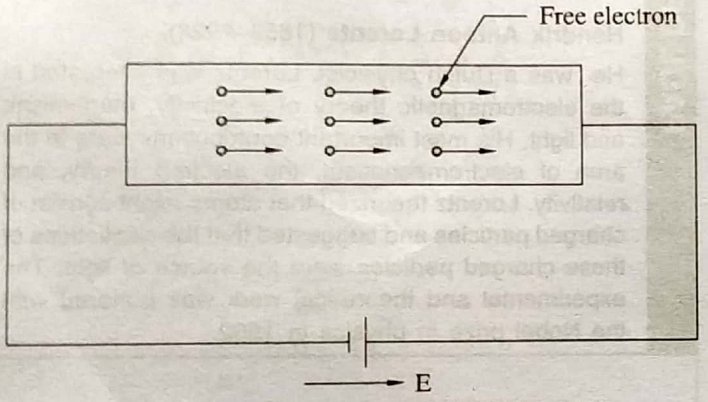


FIG. 1.10 : METAL – CONDUCTION

- The force experienced by an electron with charge q in an electric field E is given by

$$\boxed{F = q \cdot E} \quad \text{... (1)}$$

where, E = Applied electric field
q = Charge of an electron

and acceleration,

$$a = \frac{\text{Force}}{\text{Mass}} = \frac{F}{m} = \frac{q \cdot E}{m} \quad \text{... (2)}$$

- Integrating Equation (2), we get,

$$\therefore \quad \int a \, dt = \int \frac{q \cdot E}{m} dt$$

$$\therefore \quad \boxed{v = \frac{q \cdot E}{m} t + C} \quad \text{... (3)}$$

where v is the velocity of the electron, C is an integration constant, and is obtained by applying the boundary conditions. During the absence of the electric field, the average velocity of the electron is zero,

i.e., when $t = 0$, $v = 0$

- Substituting the above boundary condition in euqation (3), we get, C = 0.
- Substituting the value of C in equation (3), we get,

Velocity of the electron,

$$v = \left(\frac{q \cdot E}{m}\right) \cdot t \quad \text{... (4)}$$

$$= \left(\frac{q \cdot t}{m}\right) \cdot E$$

- Hence the average velocity is proportional to E.

$$\therefore \quad v \propto E$$

$$\therefore \quad \boxed{v = \mu E}$$

where, μ = mobility of electron and its measured in m^2/volt-sec.

Definition of Mobility :

- Mobility of a charge particle can be defined as its average velocity under the influence of a unit electric field strength.

1.8 ELECTRIC CURRENT IN A CONDUCTOR (METAL) :

- Consider a piece of a metal or conductor in which electrons are uniformly distributed as shown in Fig. 1.11.

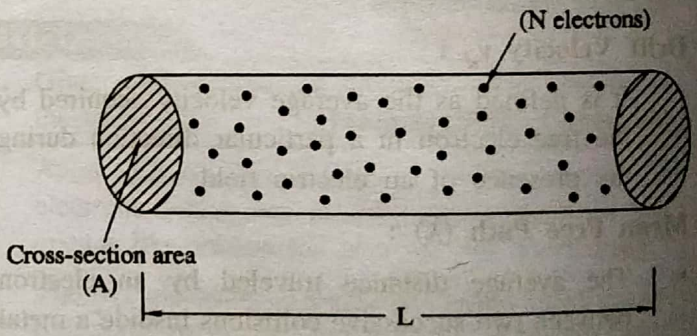


FIG. 1.11 : METAL OR CONDUCTOR

- Let, N = No. of free electrons distributed in the conductor
L = Length of the conductor
A = Cross-sectional area of the conductor
- We know that when an electric field is applied to the conductor, the electrons start moving in the semiconductor. Therefore, the average velocity of the electrons

$$v = \frac{L}{T}$$

where, T is the time taken by the electrons to travel through a distance.

- The number of electrons passing through any area per second,

$$= \frac{N}{T}$$

∴ Total charge passing through any area per second (i.e., current)

I = charge × number of electrons per second passing through any area

$$= q \times \frac{N}{T}$$

$$= q \times \frac{N}{T} \cdot \frac{L}{L}$$

$$= \boxed{\frac{q \cdot N \cdot v}{L}}$$

- Thus, the current in conductor,

$$I = \frac{q \cdot N \cdot v}{L}$$

$$J = \frac{I}{A} = \frac{q \cdot N \cdot v}{A \cdot L}$$

$$\left\{\because \text{ current density } \left(J = \frac{I}{A}\right)\right\}$$

$$J = q \cdot \left(\frac{N}{LA}\right) \cdot v$$

$$\left\{n = \frac{N}{LA} = \text{Concentration of electrons per unit volume}\right\}$$

$$\boxed{J = q \cdot n \cdot v}$$

1.8.1 Electrical Conductivity (σ) of a Conductor :

- From the relation of current density,

$$\boxed{J = q \cdot n \cdot v} \qquad \dots (1)$$

- Also current density J (i.e. electric current per unit area) is given by the relation.

$$\boxed{J = \sigma \cdot E} \qquad \dots (2)$$

where, σ = Conductivity of a metal

E = Applied electric field

Now, compair equation (1) with (2), we get

$$\therefore \quad q \cdot n \cdot v = \sigma \cdot E$$

$$\therefore \quad q \cdot n \cdot (\mu \cdot E) = \sigma \cdot E$$

$$\therefore \quad q \cdot n \cdot \mu = \sigma$$

$$\therefore \quad \sigma = q \cdot n \cdot \mu$$

Also, $\boxed{\sigma = \frac{1}{\rho} = q \cdot n \cdot \mu}$

where, ρ = Resistivity of a metal

μ = Mobility of a metal.

1.9 THERMAL CONDUCTIVITY (K) :

- Thermal conductivity (K) of a material is equal to the amount of heat energy (Q) conducted per unit area of cross-section per second to the temperature gradient $\left(\frac{dT}{dx}\right)$.

i.e. $$Q \propto \frac{dT}{dx}$$

$$\therefore \quad Q = K\frac{dT}{dx}$$

Therefore, thermal conductivity

$$K = \frac{Q}{\left(\frac{dT}{dx}\right)} \qquad \dots (1)$$

- In solids, the conduction takes place both by available free electrons and thermally excited lattice vibrations known as phonons.
- Therefore, the total conductivity is

$$\boxed{K_{total} = K_{electrons} + K_{phonons}} \qquad \dots (2)$$

where phonons are the energy carriers for lattice vibrations.

Metals :

- In case of metals, the concentration of free electrons is very high. Therefore, electrons, in addition to thermal vibrations, absorb and transport thermal energy. Hence, the thermal conductivity of a metal is due to the free electrons. ($K_{electrons} >> K_{phonons}$),

$$\boxed{K_{total} = K_{electrons}} \qquad \dots (3)$$

Insulators :

- In insulators, the thermal conductivity is due to atomic or molecular vibration of the lattice,

i.e. $$\boxed{K_{total} = K_{phonons}} \qquad \dots (4)$$

Semiconductors :

- The thermal conductivity is due to both electrons and phonons.

Therefore,

$$\boxed{K_{total} = K_{electrons} + K_{phonons}} \qquad \dots (5)$$

1.10 VERIFICATION OF OHM'S LAW :

- The free electron theory is used to verify Ohm's law.
- In order to verify the same, consider that the steady-state current density can be written as

$$J = \sigma E \quad \text{... (1)}$$

- We know that the current density $J = I/A$, the conductivity $\sigma = 1/\rho$, and the electric field intensity $E = V/d$. Therefore, equation (1) is given by

$$\frac{I}{A} = \frac{1}{\rho} \cdot \frac{V}{d}$$

$$\therefore \quad \boxed{V = \left(\frac{\rho d}{A}\right) I} \quad \text{... (2)}$$

We know that,

$$\rho = \frac{RA}{d} \quad \text{and hence,}$$

$$\therefore \quad R = \frac{\rho d}{A} \quad \text{... (3)}$$

- Substituting the above value in equation (2), we get,

$$\boxed{V = IR} \quad \text{... (4)}$$

- Equation (4) states the Ohm's law. It is clear from the above equation that Ohm's law is verified using free electron theory.

1.11 FREE ELECTRON THEORY – ADVANTAGES AND DRAWBACKS :

GTU, January-2019

GTU Questions

1. Give success and drawback of classical free electron theory. **[January-2019, 3-Marks]**

Advantages :

(1) It explains the electrical conductivity and thermal conductivity of metals.

(2) It verifies Ohm's law.

(3) It is used to explain the optical properties of metals.

Drawbacks :

(1) It fails to explain the electric specific heat and the specific heat capacity of metals.

(2) It fails to explain superconducting properties of metals.

(3) It fails to explain new phenomena like photoelectric effect.

(4) It fails to explain electrical conductivity of semiconductors or insulators.

(5) The free electron model predicts the incorrect temperature dependence of σ. According to the free electron theory, $\sigma \propto T^{-1}$.

(6) It fails to give a correct mathematical expression for thermal conductivity.

(7) Ferromagnetism couldn't be explained by this theory.

(8) Susceptibility has greater theoretical value than the experimental value.

1.12 ENERGY LEVEL :

- Each orbit has fixed amount of energy associated with it.
- The electrons moving in particular orbit possess the energy of that orbit. The larger the orbit, the greater is its energy. It becomes clear that outer orbit possess more energy than the inner orbit electrons.
- A convenient way of representing the energy of different orbit is shown in Fig. 1.12. This is known as energy level diagram.

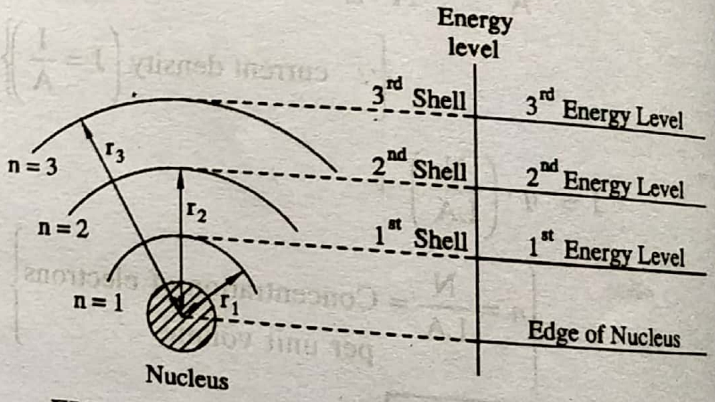


FIG. 1.12 : CONCEPT OF ENERGY LEVEL

- The first represents the first energy level, the second orbit indicates the second energy level and so on.
- The larger the orbit of an electron, the greater is its energy and higher is the energy level.

1.13 ENERGY BAND :

- In case of single isolated atom, the electrons in any orbit possess definite energy. However, an atom in a solid is great influenced by the closely-packed neighbouring atoms. The result is that the electron in any orbit of such an atom can have a range of energies rather than a single energy. This is known as energy band.

- The range of energies possessed by an electron in a solid is known as energy band.

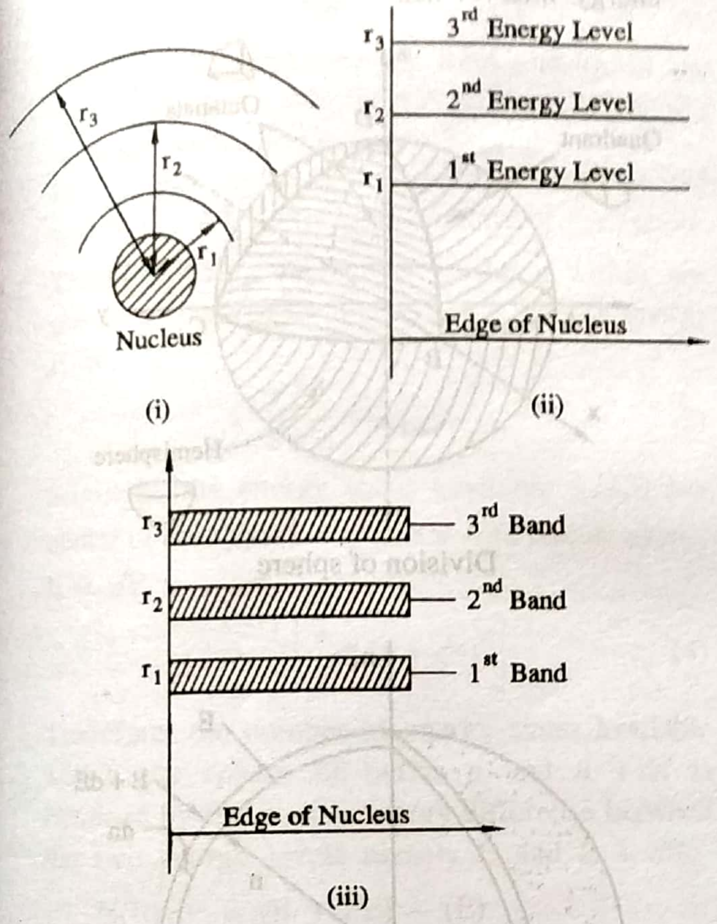


FIG. 1.13 : ENERGY BAND

- Each orbit of an atom has a single energy. Therefore, an electron can have only single energy corresponding to the orbit in which it exists.
- However, when the atom is in a solid, the electron in any orbit can have a range of energies. For instance, electrons in first orbit have slightly different energies because no two electrons in this orbit see exactly the same charge environment.
- Since, there are millions of first orbit electrons, the slightly different energy levels form a band, called 1st energy band (see Fig. 1.13).
- The electrons in the first orbit can have any energy range in this band. Similarly, second orbit electrons form second energy band and so on.

1.13.1 Important Energy Band in Solids :

- There are a number of energy bands in solids, the following are of particular important energy band in solids (see Fig. 1.14).

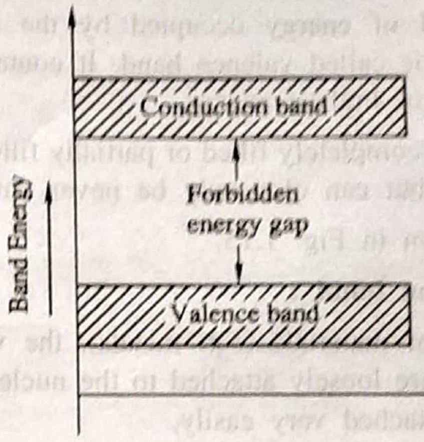


FIG. 1.14 : ENERGY BAND IN SOLIDS

1. **Valence band :**

- The range of energies (i.e., band) possessed by valence electrons is known as valence band.

2. **Conduction band :**

- The range of energies (i.e., band) possessed by conduction electrons is known as conduction band.

3. **Forbidden energy gap :**

- The separation between conduction band and valence band on energy level diagram is known forbidden energy gap.

Syllabus Topic : Energy Band Diagram

1.14 ENERGY BAND DIAGRAM :

- The graphical representation of the energy band diagram is shown in Fig. 1.15.

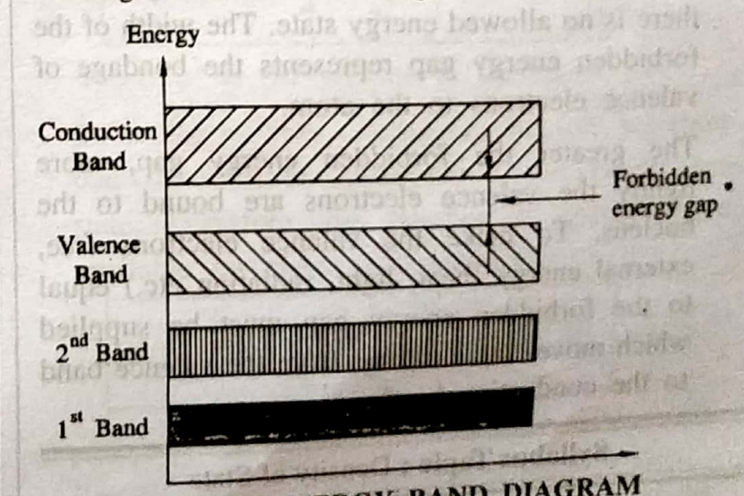


FIG. 1.15 : ENERGY BAND DIAGRAM

- The are three type of energy bands as given below :

1. **Valence band :**

- The electrons in the outermost orbit of an atom are known as valence electrons.

- The band of energy occupied by the valence electrons is called valence band. It contains the electrons of highest energy.
- It may be completely filled or partially filled with electrons but can obviously be never empty.
- It is shown in Fig. 1.15.

2. **Conduction band :**

- In some of materials (e.g. metals), the valence electrons are loosely attached to the nucleus and can be detached very easily.
- These electrons are known as free electrons. These electrons are responsible for the conduction of current.
- For this reason, these electrons are also known as conduction electrons.
- The energy band occupied by the conduction (or free) electrons is called conduction band, which is shown in Fig. 1.15.
- It may either be empty or partially filled. If a substance has empty conduction band, it means conduction of current is not possible in that substance and it is known as insulator.

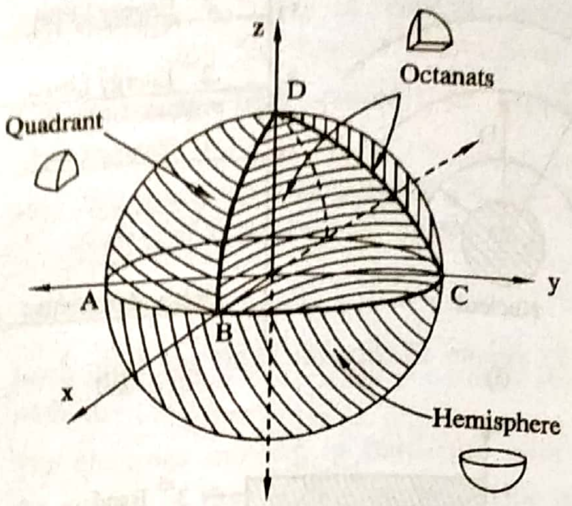
3. **Forbidden energy gap :**

- The energy gap between the valence band and conduction band is known as forbidden energy gap. It is shown in Fig. 1.15.
- It is a region in which no electron can stay because there is no allowed energy state. The width of the forbidden energy gap represents the bondage of valence electrons to the atom.
- The greater the forbidden energy gap, more tightly the valence electrons are bound to the nucleus. To make the valence electrons free, external energy (heat, light, radiation etc.) equal to the forbidden energy gap must be supplied which moves the electrons from the valence band to the conduction band.

Syllabus Topic : Density of State

1.15 DENSITY OF STATES :

- 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) *d*E is defined as the number of energy states N(E) *d*E per unit volume in an energy interval *d*E.



Division of sphere

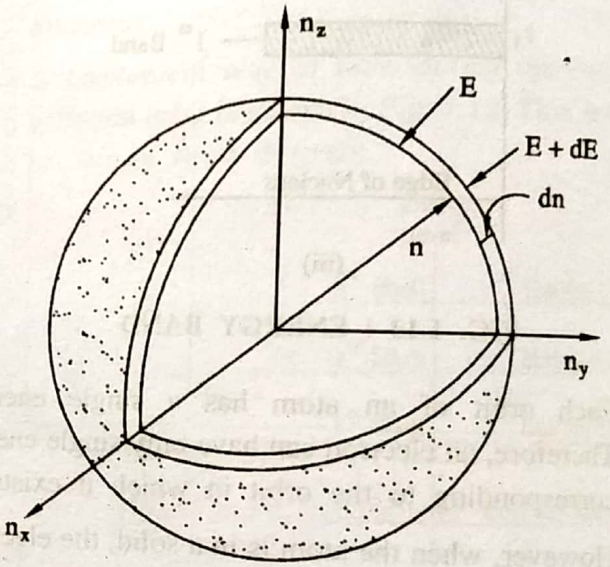


FIG. 1.16 : SPHERES SHOWING DENSITY OF STATES IN *n*-SPACE

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

- Consider that the sphere is further divided into number shells as shown in Fig. 1.16.
- Therefore, each shell is represented by a set of quantum numbers (n_x, n_y 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

$$n^2 = n_x^2 + n_y^2 + n_z^2 \quad \dots (2)$$

- 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

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

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

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

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

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

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

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

- Simplifying the above equation (5) using $(a + b)^3 = a^3 + b^3 + 3a^2b + 3ab^2$, we get,

$$N(E)\, d(E) = \frac{\pi}{6}\left(dn^3 + 3n^2\, dn + 3ndn^2\right)$$

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

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

- Simplify the above equation, we get,

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

$$\therefore \boxed{N(E)\, dE = \frac{\pi}{2} n\, (ndn)} \qquad \text{... (7)}$$

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

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

- Rearranging the above equation, we get,

$$n^2 = \frac{8ma^2}{h^2}\, dE \qquad \text{... (8)}$$

$$\therefore \boxed{n = \left[\frac{8ma^2E}{h^2}\right]^{1/2}} \qquad \text{... (9)}$$

- The value of ndn is obtained by differentiating equation (9), we get

$$\text{i.e.,} \quad 2ndn = \frac{8ma^2}{h^2}\, dE \qquad \text{... (10)}$$

$$\therefore \boxed{ndn = \frac{8ma^2}{2h^2}\, dE} \qquad \text{... (11)}$$

- Substituting the value of n and ndn from the equation (10) and (11) in equation (7) we get,

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

- Simplifying the above equation, we get,

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

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

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

$$[\because \text{ unit volume, } a^3 = 1] \qquad \text{... (12)}$$

- Equation (12) is the effective number of energy states in a volume a^3 with energy between E and $E + dE$. The number of available energy states per unit volume $a^3 = 1$.
- We know that,

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

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

  Density of states

$$\boxed{Z(E)\ dE = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{3/2} E^{1/2}\, dE} \quad \dots (13)$$

- Equation (13) is the density of energy states i.e., 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,

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

i.e., the density of states curve is a parabola as shown in Fig. 1.17.

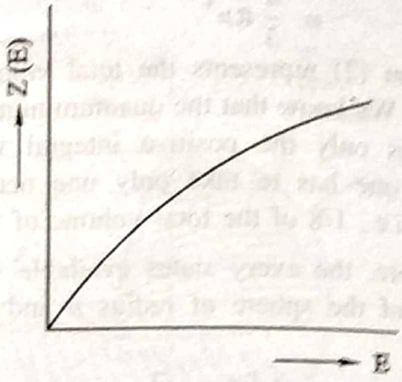


FIG. 1.17 : VARIATION OF THE DENSITY OF STATES WITH ELECTRON ENERGY

Syllabus Topic : Kronig Penny Model

1.16 KRONIG PENNY MODEL :

GTU, January-2019

GTU Questions

1. Explain Kronig Penney model in detail. **[January-2019, 7-Marks]**

- According to free electron theory of metals, a conduction electron in a metal experiences constant (or zero) potential and free to move inside the crystal but will not come out of the metal because an infinite potential exists at the surface.
- Free electron theory successfully explains electrical conductivity, specific heat, thermionic emission and paramagnetism.
- Free electron theory is fails to explain many other physical properties, for example : (1) it fails to explain the difference between conductors, insulators and semiconductors, (2) positive Hall coefficient of metals.
- Consider the one dimensional periodic arrangement of positively charged ions inside a crystal as shown in Fig. 1.18.
- The motion of the free electrons inside the positively charged ion core is shown in Fig. 1.18(a).
- The potential energy of the freely moving electron at the positive ion site inside the crystal is zero while it is maximum at the middle.
- On the other hand, outside the crystal, the potential energy is infinite. Therefore, the potential energy of the moving electrons varies periodically with same period as that of crystal as shown in Fig. 1.18(b).

RALPH KRONIG & WILLIAM PENNEY

Ralph Kronig

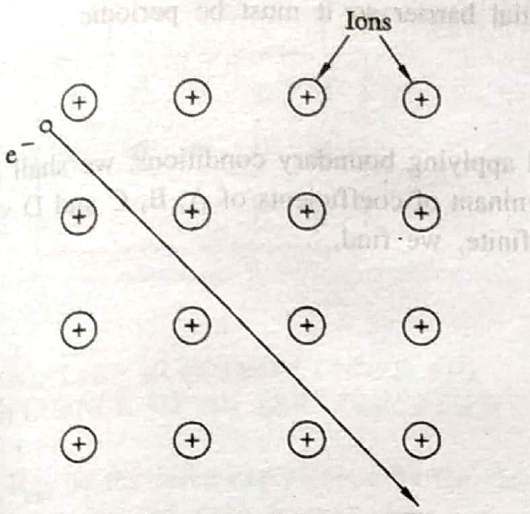
William Penney

Ralph Kronig (1904–1995)

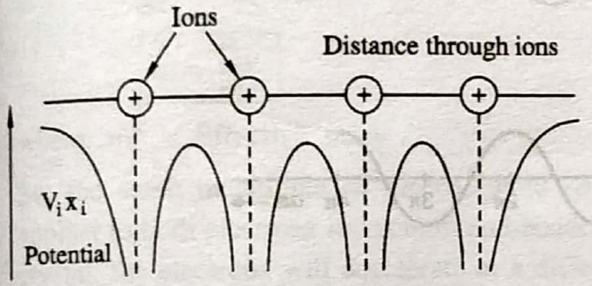
He was a German American physicist. He is noted for the discovery of particle spinand for his theory of x-ray absorption spectroscopy. His theories include the Kronig–Penney model, the Coster–Kronig transition and the Kramers–Kronig relations. The Kronig-Penney Model (1931) is a one-dimensional model of a crystal that shows how the electrons in a crystal are dispersed into allowed and forbidden bands by scattering from the extended linear array of atoms.

William George Penney, (1909 –1991).

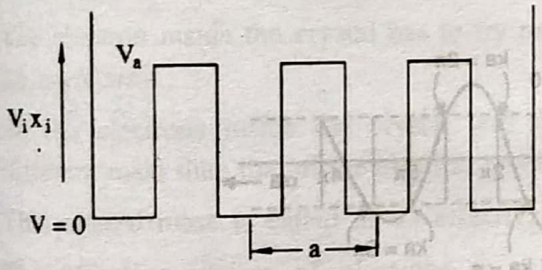
He was an English mathematician and professor of mathematical physics at the Imperial College London. He had made significant contributions to the application of collisions, explosion events that created shock waves.



(a) Motion of Electron



(b) Potential energy variation



(c)

FIG. 1.18 : ONE DIMENSIONAL PERIODIC POTENTIAL

- It is not easy to solve Schrodinger's equation with these potentials. So, Kronig and Penney approximated these potentials inside the crystal to the shape of rectangular steps and shown in Fig. 1.18(c).
- This model is called Kronig Penney model of potentials.
- Solution of Schrodinger's equations in the periodic potential offered by *atomic ions* to moving electrons predicts existence of allowed energy bands separated by energy band gaps. This was observed by Kronig and Penny.
- Assuming atomic-ions to be at rest and a single electron moving through the periodic potential as shown in Fig. 1.19 such that it is zero at atomic site. The potential has periodicity.

$$V(x) = V(x + a + b) \qquad \dots (1)$$

$$V(x) = 0 \text{ for } 0 < x < a$$

and $$V(x) = V_0 \text{ for } -b < x < 0$$

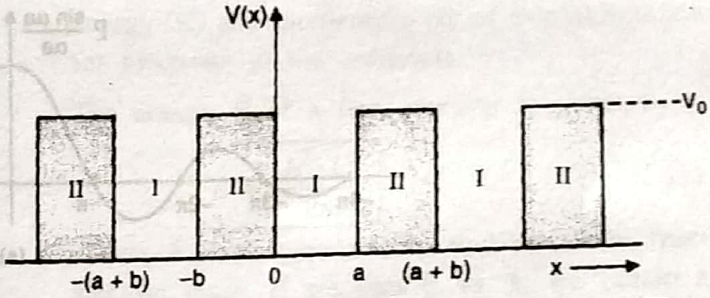


FIG. 1.19 : PERIODIC POTENTIAL IN WHICH ELECTRONS MOVE IN A SOLID AS PER K.P. MODEL $V_0 \to \infty$ BUT $V_0 a$ = FINITE. POTENTIAL IS TAKEN AS ZERO AT THE SITE OR ATOM-ION

- The Schrodinger's equations in the two regions are given by

Region-I $(0 < x < a)$

$$\frac{d^2\psi_1}{dx^2} + \frac{2mE}{h^2} = 0 \qquad \dots (2)$$

Region-II $(-b < x < 0)$

$$\frac{d^2\psi_2}{dx^2} + \frac{2m(E + V_0)}{h^2}\psi_0 = 0 \qquad \dots (3)$$

- Defining two positive constants α and β as

$$\alpha = \sqrt{\frac{2mE}{h^2}} \qquad \dots (4)$$

and $$\beta = \sqrt{\frac{2m(V_0 - E)}{h^2}} \qquad \dots (5)$$

- The general solutions of equation (2) and (3) are

$$\psi_1 = Ae^{i\alpha x} + Be^{-i\alpha x} \qquad \dots (6)$$

$$\psi_{11} = Ce^{\beta x} + De^{-\beta x} \qquad \dots (7)$$

- Constants A, B, C and D have to be found using boundary conditions that ψ and $\frac{d\psi}{dx}$ are continuous at the boundary of potential barrier.

- Since wave function has to be symmetric to the potential barrier so it must be periodic

$$\Psi_{(x)} = e^{ikx}\, u_k(x) \qquad \text{... (8)}$$

where, $u_k(x) = u_k\,(x + a + b)$ ... (9)

- Substituting with equation (8) and (9) in (6) and (7) and applying boundary conditions, we shall get four equations. These have non-vanishing solution when determinant of coefficients of A, B, C and D vanishes. Under the assumption that $V_0 \rightarrow \infty$ but V_0a remains finite, we find,

$$\boxed{P\frac{\sin \alpha a}{\alpha a} + \cos \alpha a = \cos ka} \qquad \text{... (10)}$$

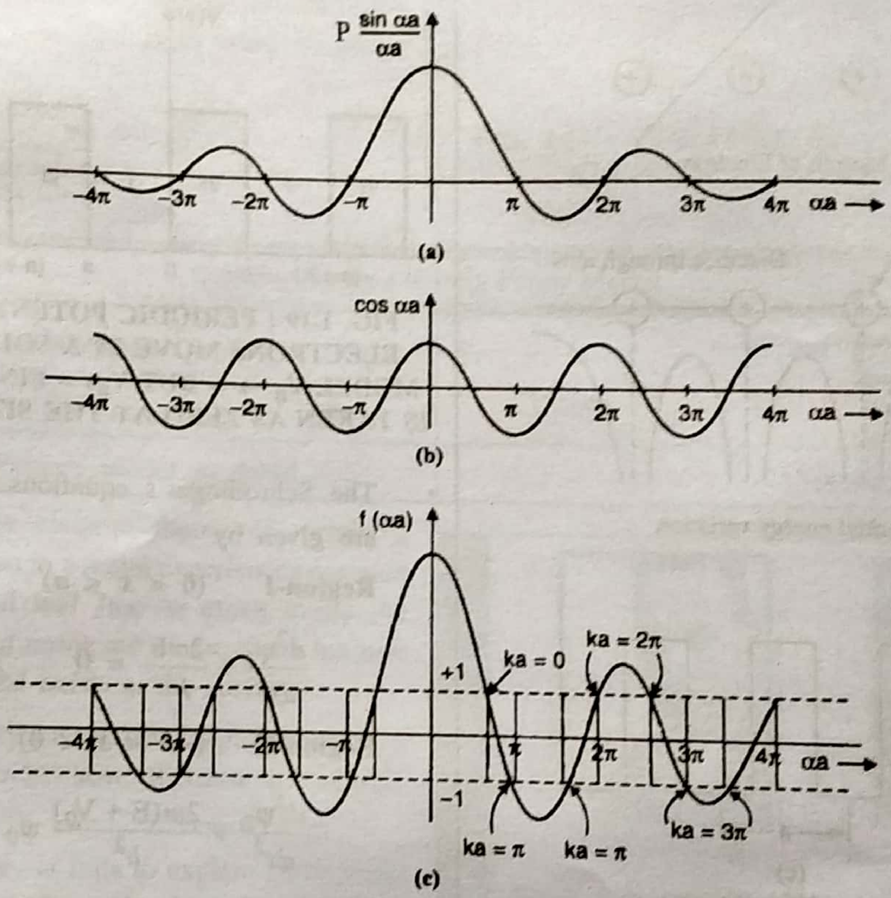


FIG. 1.20 : A PLOT OF (a) THE FIRST TERM IN EQUATION (10), (b) THE SECOND TERM IN EQUATION (10) AND (c) THE ENTIRE $f(\alpha a)$ FUNCTION. THE SHADED AREAS SHOW THE ALLOWED VALUES OF (αa) CORRESPONDING TO REAL VALUES OF K

1.17 EFFECTIVE MASS OF AN ELECTRON :

- Let an external field E is applied on the electron when it is in a vacuum shown in Fig. 1.21.

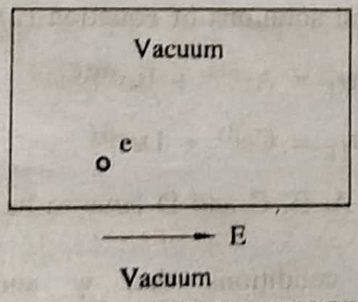


FIG. 1.21 : ELECTRON UNDER THE INFLUENCE OF AN ELECTRIC FIELD

- Let F_{ext} be the force experienced by the electron when an external field is applied in a vacuum.

$$\therefore \quad F_{ext} = m \cdot a$$

$$\therefore \quad \boxed{a = \frac{F_{ext}}{m}} \qquad \text{... (1)}$$

- Let the an external field E is applied to the electron when it is in a crystal shown in Fig. 1.22.

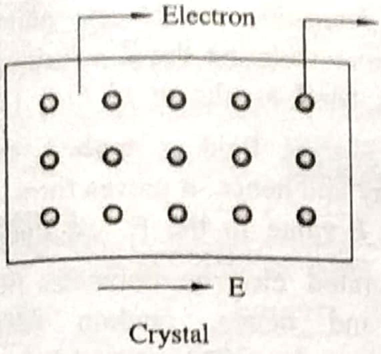


FIG. 1.22 : ELECTRON UNDER THE INFLUENCE OF AN ELECTRIC FIELD

- Let F_{ext} be the force experienced by the electron when an external field is applied in a crystal.

$$\therefore \quad F_{ext} = m^* \cdot a$$

$$\therefore \quad \boxed{a = \frac{F_{ext}}{m^*}} \quad \dots (2)$$

where, m^* = Effective mass

- So, the same magnitude of electric field (E) is applied to both electrons in vacuum and inside the crystal, the electrons will accelerate at a different rate from each other due to the existence of different potentials inside the crystal.
- The electron inside the crystal has to try to make its own way.
- So the electrons inside the crystal will have a different mass than that of the electron in vacuum.
- This altered mass is called as an effective-mass.
- The effective masses of electrons in different metals are shown in Table-1.

Table-1 : Effective masses of electrons in different metals

Metals	m^*/m
Cu	1.010
Ag	0.990
Au	1.100
Bi	0.047
K	1.120
Li	1.280
Na	1.200
Ni	28.000
Pt	13.000
Zn	0.850

Syllabus Topic : E – k Diagram

1.18 E – k DIAGRAM :

- The sign of the effective mass (m^*) is determined directly from the E-k diagram.
- An E – k diagram shows characteristics of a particular semiconductor material.
- E – k diagram shows the relationship between the energy (E) and momentum (k) of available states for electrons in the materials.
- The energy E of a free electron is given by

$$\boxed{E = \frac{h^2 \cdot k^2}{2m}} \quad \dots (1)$$

where, k is the momentum and m is the free-electron mass. If we plot E vs. k, we obtain a parabola as shown in Fig. 1.23.

- In a semiconductor crystal, an electron in the conduction band is similar to a free electron in the it is relatively free to move about in the crystal.
- However, because of the periodic potential of the nuclei, equation (1) can no longer be valid.
- However, it turns out that we can still use equation (1) if we replace the free-electron mass in equation (2) by an effective mass m^*.

$$\boxed{E = \frac{h^2 \cdot k^2}{2m^*}} \quad \dots (2)$$

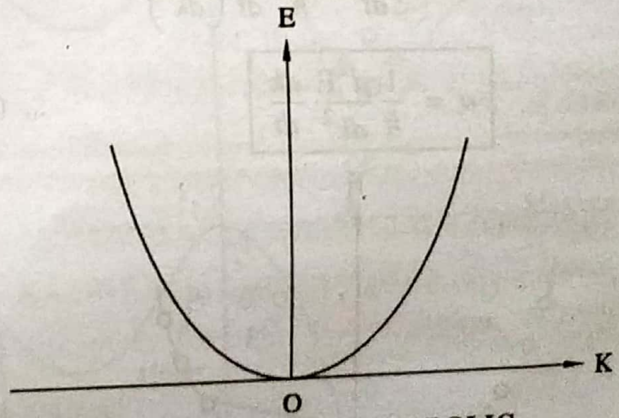


FIG. 1.23 : THE PARABOLIC ENERGY (E) VS. MOMENTUM (K) CURVE FOR A FREE ELECTRON

1.19 EQUATION FOR EFFECTIVE MASS :

- Consider an electric field of strength E is applied to the crystal.

- The force exerted by the electron in the crystal is

$$F = -q \cdot E$$

$$= ma \quad \text{... (1)}$$

- According to quantum concept, the electrons behaves as a wave and hence, the group velocity is

$$\boxed{v_g = \frac{d\omega}{dk}} \quad \text{... (2)}$$

where, ω is the angular frequency, k is known as wave vector or wave number and its value is equal to $2\pi/\lambda$.

- We know that the energy of the electron

$$E = h\,\omega \quad \text{... (3)}$$

- Differentiating the above equation, we get,

$$dE = h\,d\omega$$

$$\therefore \quad \boxed{d\omega = \frac{dE}{h}}$$

- Substituting the value of $d\omega$ in the equation (2), we get the group velocity

$$V_g = \frac{1}{h}\frac{dE}{dk} \quad \text{... (4)}$$

- The acceleration exerted by the electron is obtained by differentiating the above equation w.r.t.t,

- The acceleration exerted by the electrons

$$a = \frac{dv_g}{dt} = \frac{1}{h} \cdot \frac{d}{dt}\left(\frac{dE}{dk}\right)$$

$$\therefore \quad \boxed{a = \frac{1}{h}\frac{d^2E}{dk^2}\frac{dk}{dt}} \quad \text{... (5)}$$

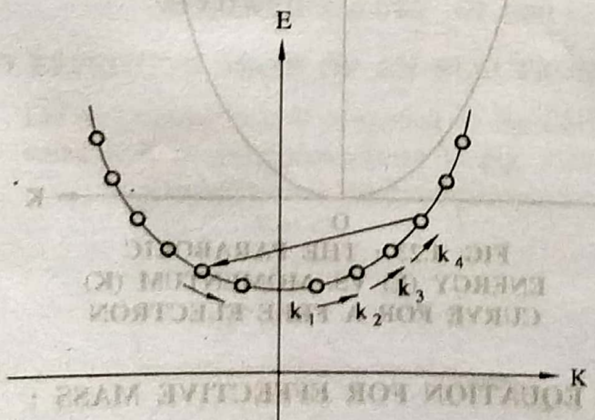


FIG. 1.24 : E – k DIAGRAM OF CONDUCTION BAND

- One can determine the energy gained by the electron by considering the E – k diagram of the conduction band as shown in Fig. 1.24.

- When an electric field is applied, the electron gains energy and hence, it moves form one k value to another k value in the E – k diagram.

- The accelerated electron coincides with lattice vibration and hence, random scattering of electrons takes place. The scattered electron takes into another k value as shown in Fig. 1.24.

- Thus, the group velocity of the electron is determined from the gradient of the E – k diagram.

- Let F_{ext} be the external force acting on the electron by the application of external field.

- The distance moved by the electron when it acquires energy externally is dt. Therefore, the energy gained by the electron

$$dE = F_{ext}\, v_g\, dt \quad \text{... (6)}$$

- Rearranging the above equation, we get,

$$F_{ext} = \frac{1}{v_g}\frac{dE}{dt} \quad \text{... (7)}$$

- Substituting the value of V_g from equation (4) in the above equation, we get,

$$F_{ext} = h\frac{dk}{dt}$$

$$\therefore \quad \boxed{\frac{dk}{dt} = \frac{F_{ext}}{h}} \quad \text{... (8)}$$

- Substituting the value of $\frac{dk}{dt}$ from equation (8) in equation (5), we get,

$$a = \frac{F_{ext}}{h^2\left[\frac{d^2E}{dk^2}\right]^{-1}} \quad \text{... (9)}$$

- Comparing the value of a with $a = \frac{F}{m}$, we get,

$$\boxed{\frac{F}{m} = \frac{F_{ext}}{h^2\left[\frac{d^2E}{dk^2}\right]^{-1}} = \frac{F_{ext}}{m^*}} \quad \text{... (10)}$$

where, $m^* = h^2\left[\frac{d^2E}{dk^2}\right]^{-1}$ known as the effective mass of the electron and it depends on the E – k d diagram.

Syllabus Topic : Direct and Indirect band gaps

1.20 DIRECT AND INDIRECT BAND GAPS :

GTU, January-2019

GTU Questions

1. Explain direct and indirect band gap with E-k diagrams. **[January-2019, 7-Marks]**

1. Band Gap :

- The band gap represents the minimum energy difference between the top of the valence band and the bottom of the conduction band.
- However, the top of the valence band and the bottom of the conduction band are not generally at the same value of the electron momentum.

2. Direct Band Gap :

- In a direct band gap semiconductor, the top of the valence band and the bottom of the conduction band occur at the same value of momentum, as in the schematic below.

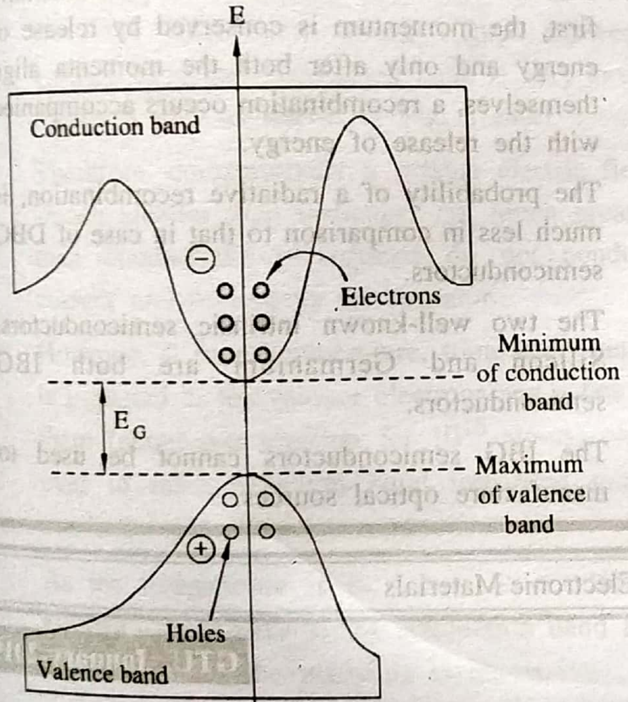


FIG. 1.25(a) : DIRECT BAND GAP

- When an electron sitting at the bottom of the conduction Band recombines with a hole sitting at the top of the Valance Band, there will be no change in momentum values.
- Energy is conserved by means of emitting a photon, such transitions are called as radiative transitions.

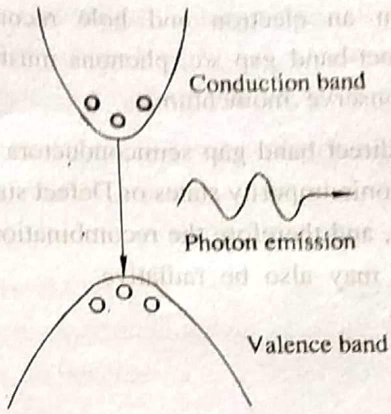


FIG. 1.25(b) : DIRECT BAND GAP

- Direct band gap semiconductors are capable of photon emission, by radiative recombination, but indirect semiconductors have a low probability of radiative recombination.

3. Indirect Band Gap :

- In an indirect band gap semiconductor, the maximum energy of the valence band occurs at a different value of momentum when comparing with the minimum in the conduction band.

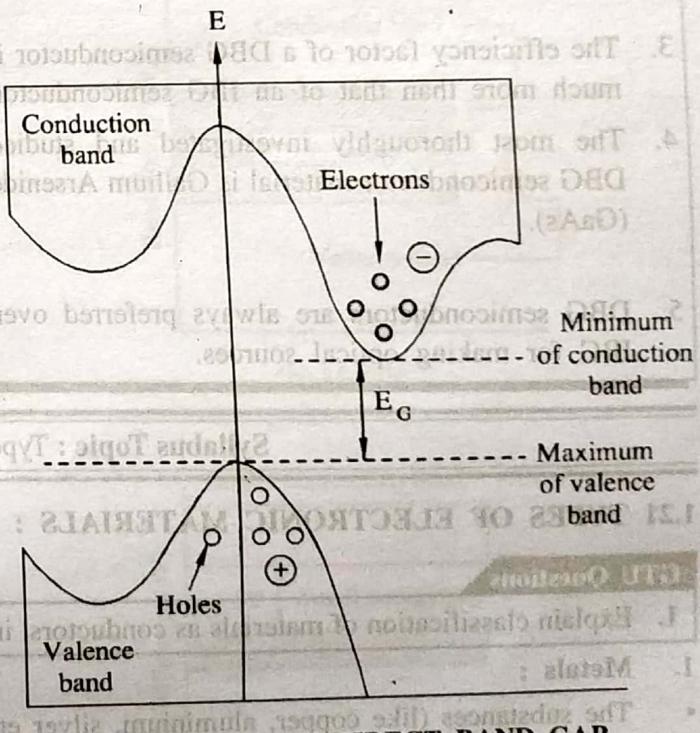


FIG. 1.25(c) : INDIRECT BAND GAP

- For an indirect-band gap material; the minimum of the conduction band and maximum of the valance band lie at different k-values.

- When an electron and hole recombine in an indirect-band gap s/c, phonons must be involved to conserve momentum.
- In indirect band gap semiconductors may have is electronic impurity states or Defect state which are direct, and therefore the recombination from these states may also be radiative.

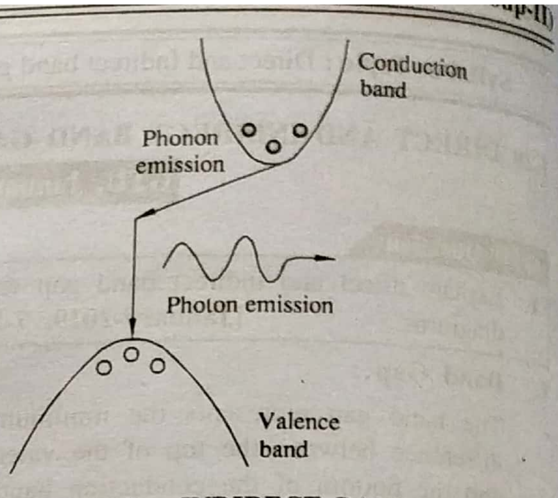


FIG. 1.25(d) : INDIRECT BAND GAP

Direct Band Gap (DBG) Semiconductor	Indirect Band Gap (IBG) Semiconductor
1. A direct band-gap (DBG) semiconductor is one in which the maximum energy level of the valence band aligns with the minimum energy level of the conduction band with respect to momentum.	1. A indirect band-gap (DBG) semiconductor is one in which the maximum energy level of the valence band are misaligned with the minimum energy level of the conduction band with respect to momentum.
2. In a DBG semiconductor, a direct recombination takes place with the release of the energy equal to the energy difference between the recombining particles.	2. Due to a relative difference in the momentum, first, the momentum is conserved by release of energy and only after both the momenta align themselves, a recombination occurs accompanied with the release of energy.
3. The efficiency factor of a DBG semiconductor is much more than that of an IBG semiconductor.	3. The probability of a radiative recombination, is much less in comparison to that in case of DBG semiconductors.
4. The most thoroughly investigated and studied DBG semiconductor material is Gallium Arsenide (GaAs).	4. The two well-known intrinsic semiconductors, Silicon and Germanium are both IBG semiconductors.
5. DBG semiconductors are always preferred over IBG for making optical sources.	5. The IBG semiconductors cannot be used to manufacture optical sources.

Syllabus Topic : Types of Electronic Materials

1.21 TYPES OF ELECTRONIC MATERIALS :

GTU, January-2019

GTU Questions

1. Explain classification of materials as conductors, insulators and semiconductors. **[January-2019, 7-Marks]**

1. Metals :

- The substances (like copper, aluminium, silver etc.) which allow the passage of current through them are known as conductors.
- These materials have free electrons for electrical conduction. In terms of energy bands, the valence band of these substances overlap the conduction band as shown in Fig. 126(b).
- Due to this overlapping, a large number of free electrons are available for conduction. In fact, there is no physical distinction between the two bands.

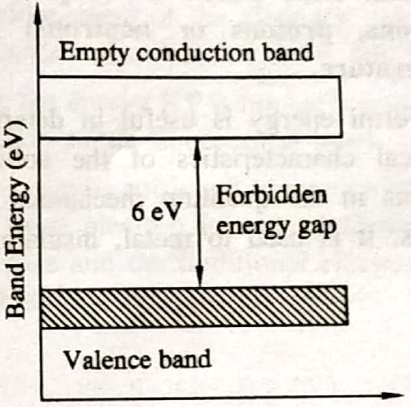
- Hence, the availability of large number of conduction electrons is possible.
- This is the reason why a slight electric field applied across such substances causes a heavy flow of current through them.
- Another worthnoting point is that in the absence of forbidden energy band in good conductors, there is no structure to establish holes. The total current in such conductors is simply a flow of electrons.

2. **Semiconductors :**

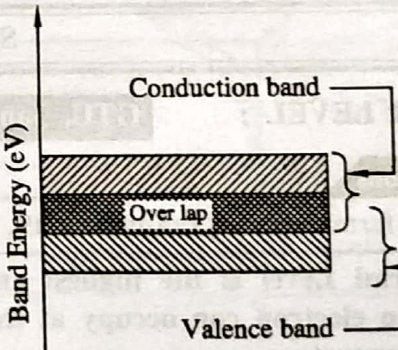
- The substances like carbon, silicon, germanium etc. whose electrical conductivity lies in between the conductors and insulators are known as semiconductors.
- Although the valence band of these substances is almost filled and conduction band is almost empty as in the case of insulators.
- But the forbidden energy gap between valence band and conduction band is very small (nearly 1 eV) as shown in Fig. 1.26(c).
- Therefore, comparatively a smaller electric field (much smaller than insulators but much greater than conductors) is required do not conduct current and behave as an insulator.
- However, at room temperature, some heat energy is imparted to the valence electrons and a few of them (about one electron for 10^{10} atoms) cross over to the conduction band imparting minor conductivity to the semiconductors.
- As the temperature is increased, more valence electrons cross over to the conduction band and conductivity of the materials increases.

3. **Insulators :**

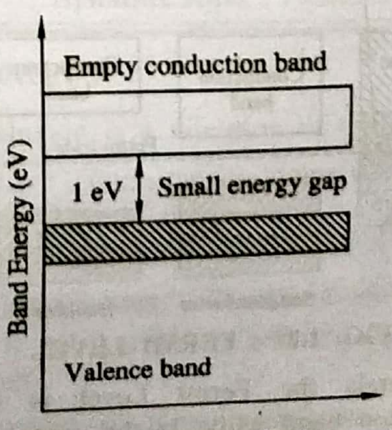
- The substances (like wood, glass, mica etc.) which donot allow the passage of current through them are known as insulators.
- The valence band of these substances is full whereas the conduction band is completely empty. Valance electrons are bound very tightly to their parent atoms.
- So the forbidden energy gap between the valence band and the conduction band is very large (nearly 6 eV) as shown in Fig. 1.26(a).
- Therefore a large amount of energy i.e. a very high electric field is required to push the valence electrons to the conduction band.
- This is the reason why such materials under ordinary conduction do not conduct at all and are known as insulators.



(a) Insulator



(b) Metals



(c) Semiconductor

FIG. 1.26 : ENERGY BANDS IN SOLIDS

1.22 FERMI ENERGY :

- In physics there are several types of energies associated with the atom, like heat energy, electrical energy, light energy etc.
- But we know that the atoms and molecules can be described by quantum mechanics. The quantum mechanics is very tricky and complex field.
- In the quantum mechanics the scientists rely on the Fermi energy to define the energy of the electrons of protons.
- **The Fermi energy is the energy of the highest level of quantum state which is occupied by the fermions (like electrons, protons or neutrons) at the absolute zero temperature.**
- The Fermi energy is useful in determining the thermal and electrical characteristics of the solids. It is the important concepts in the quantum mechanics and the superconductor physics. It is used to metal, insulators and semi-conductors.

ENRICO FERMI


Enrico Fermi

Enrico Fermi (1901 –1954)

He was an Italian and naturalized-American physicist and the creator of the world's first nuclear reactor. Fermi held several patents related to the use of nuclear power, and was awarded the 1938 Nobel Prize in Physics . Fermi followed with a paper in which he applied the principle to an ideal gas, employing a statistical formulation now known as Fermi–Dirac statistics. Today, particles that obey the exclusion principle are called "fermions". He developed the Fermi age equation.

· **Syllabus Topic : Fermi Level**

1.23 FERMI LEVEL :

GTU, January-2019

GTU Questions

1. Explain fermi levels. **[January-2019, 4-Marks]**

- **The Fermi Level is the highest energy level which an electron can occupy at the absolute zero temperature.**
- Fermi level is in between the valence band and the conduction band.

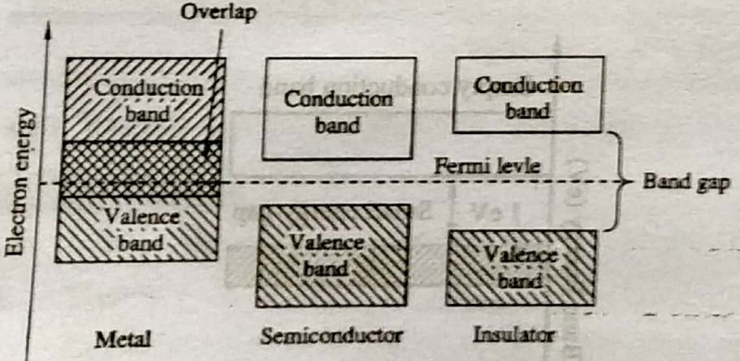


FIG. 1.27 : FERMI LEVEL

- For metals the Fermi Level is inside the conduction band while in the case of the semi conductor it exists between the conduction and the valence band at absolute zero temperature.
- In case of the insulator the large energy gap between valance band and conduction band. So it is impossible for an electron to cross it and hence the insulator acts as bad conductors.

1.24 FERMI FUNCTION :

- The Fermi Function is also known as Fermi-Dirac probability function.
- $f(E)$ is given by relation :

$$\boxed{f(E) = \frac{1}{1 + e^{\frac{(E - E_F)}{kT}}}} \quad \dots (1)$$

where, k = Boltzmann constant, eV/°K

T = Absolute Temperature

E_F = Fermi level for the crystal

E = Energy level of an allowed state

- Equation (1), the probability function $f(E)$ lies between 0 and 1. Hence, there are three possible probability namely :

$f(E) = 1$ 100% Probability to occupy the energy level by electrons.

$f(\text{E}) = 0$	No probability to occupy the energy levels by electrons and hence is empty.
$f(\text{E}) = 0.5$	50% Probability of finding the electron in the energy level.

Case-I :

- Probability of occupation at T = 0 K, and $E < E_F$.
- Substituting the above conduction in equation (1), we get

$$f(\text{E}) = \frac{1}{1+e^{-\infty}} = \frac{1}{1} = 1$$

- Therefore, $\boxed{f(\text{E}) = 1}$ ... (2)
- From equation (2), clearly indicates that at T = 0 K, the energy level below the Fermi energy level E_F is fully occupied by electrons leaving the upper levels vacant. Therefore, there is a 100% probability that the electrons to occupy energy level below Fermi energy.

Case-II :

- Probability of occupation at T = 0 K, and $E > E_F$.
- Substituting the above conduction in equation (1), we get

$$f(\text{E}) = \frac{1}{1+e^{\infty}} = \frac{1}{1+\infty} = \frac{1}{\infty}$$

- Therefore, $\boxed{f(\text{E}) = 0}$ ... (3)
- From equation (3), clearly indicates that at T = 0 K, the energy level below the Fermi energy level E_F is unoccupied i.e., vacant. Therefore, there is a 0% probability for the electrons to occupy energy level above the Fermi energy level.

Case-III :

- Probability of occupation at T = 0 and $E = E_F$.
- Substituting the above conduction in equation (1), we get

$$f(\text{E}) = \frac{1}{1+e^{0}} = \frac{1}{1+1} = \frac{1}{2} = 0.5$$

- Therefore, $\boxed{f(\text{E}) = 0.5 \text{ or } 1/2}$ ... (4)
- From equation (4), clearly indicates that at T = 0 K, there is a 50% probability for the electrons to occupy Fermi energy level.

Cash-IV :

- At High temperature (T > 0 K) i.e., $KT >> E_F$ or E_F or $T = \infty$.
- At higher temperature, electrons are excited above the Fermi energy level which is vacant.
- Therefore, most of the electrons are lying in the deep conduction band without any disturbance.
- Since, the energy KT is not sufficient to make any transition to an unoccupied level.
- This energy is sufficient to make a jump to higher level these electron lost the quantum mechanical properties and the traditional classical Boltzmann distribution function.

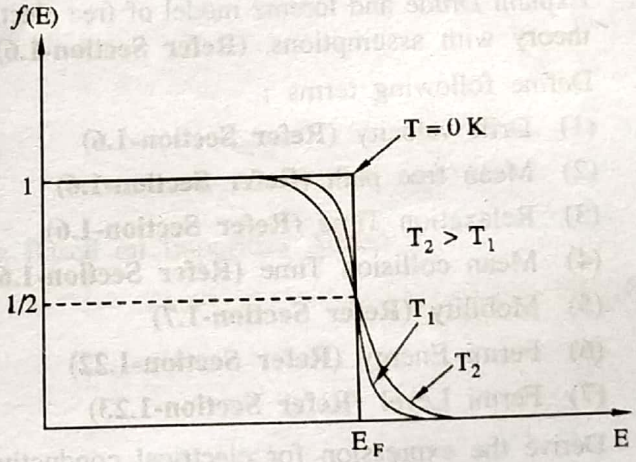


FIG. 1.28 : THE FERMI-DIRAC DISTRIBUTION FUNCTION

Syllabus Topic : Phonons

1.25 PHONON :

- The phonon is a vibration of the atomic lattice.
- In normal circumstances, atoms vibrate as a result of their thermal energy. The higher the thermal energy, the greater the vibrational energy.
- In a solid lattice, independent vibration of one atom is not possible - vibrations pass from atom to atom.
- Such vibrations pass through the whole lattice, which can vibrate as a wave at a single frequency. When this happens, the vibration is called a phonon.

- This single-frequency wave has a defined momentum and energy and can be considered to be a quantum unit or a packet of mechanical vibrational energy, just as a photon is considered to be a packet of electromagnetic energy.
- Like photons, phonons exist with discrete amounts of energy : they can only accept or lose energy in accordance with the Plank relation :

$$\boxed{\Delta E = h\nu}$$

where, ΔE = energy change,
h = Plank's constant
ν = frequency of vibration.

- Phonons can carry heat and sound through condensed states of matter – i.e. through solids and (some) liquids.
- Phonons also play a major role in determining the heat capacities of solids and liquids.

EXERCISE

1. Explain atom and its structure. **(Refer Section-1.2)**
2. What do you mean by valance electrons ? **(Refer Section-1.4)**
3. What do you mean by free electrons ? **(Refer Section-1.5)**
4. Explain free electron theory. **(Refer Section-1.6)**
5. Explain Drude and lorentz model of free electron theory with assumptions. **(Refer Section-1.6)**
6. Define following terms :
   (1) Drift velocity **(Refer Section-1.6)**
   (2) Mean free path **(Refer Section-1.6)**
   (3) Relaxation Time **(Refer Section-1.6)**
   (4) Mean collision Time **(Refer Section-1.6)**
   (5) Mobility **(Refer Section-1.7)**
   (6) Fermi Energy **(Refer Section-1.22)**
   (7) Fermi Level **(Refer Section-1.23)**
7. Derive the expression for electrical conductivity based on free electron theory. **(Refer Section-1.8)**
8. Derive the expression for thermal conductivity based on free electron theory. **(Refer Section-1.9)**
9. Explain advantages and drawbacks of free electron theory. **(Refer Section-1.11)**
10. Write short notes on energy band diagram. **(Refer Section-1.14)**
11. Derive the mathematical expression for density of states. **(Refer Section-1.15)**
12. Write short notes on Kronig Penny Model. **(Refer Section-1.16)**
13. Write short notes on E-k Diagram. **(Refer Section-1.18)**
14. What is meant by effective mass of an electron ? Drive an expression for the effective mass of an electron. **(Refer Section-1.19)**
15. Explain direct and indirect band gaps. **(Refer Section-1.20)**
16. Explain various types of electronic materials. **(Refer Section-1.21)**
17. Write short notes on :
   (1) Fermi Dirac distribution **(Refer Section-1.24)**
   (2) Fermi energy at T = 0 K and T > 0 K. **(Refer Section-1.24)**
   (3) Significance of fermi energy. **(Refer Section-1.24)**
18. What do you mean by phonon ? **(Refer Section-1.25)**

GTU QUESTIONS AND ANSWERS

1. Give assumptions of classical free electron theory. **(Refer Section-1.6)**
2. Explain Kronig Penney model in detail. **(Refer Section-1.16)**
3. Explain fermi levels. **(Refer Section-1.23)**
4. Explain classification of materials as conductors, insulators and semiconductors. **(Refer Section-1.21)**
5. Explain direct and indirect band gap with E-k diagrams. **(Refer Section-1.20)**
6. Give success and drawback of classical free electron theory. **(Refer Section-1.11)**

■ ✻ ■

CHAPTER 2

Semiconductors

Contents

2.1 INTRODUCTION TO SEMICONDUCTOR :

- The materials which having electrical resistivity in between conductor and insulator is called as semiconductors.
- The resistivity of semiconductors lie inthe range of 10^{-6} to 10^{8} Ω m.
- Silicon (Si), germanium (Ge) and graphite are some examples of semiconductors.

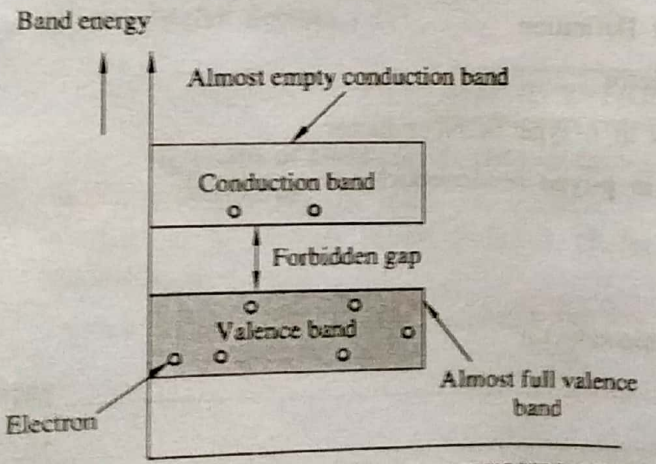


FIG. 2.1 : ENERGY BAND OF SEMICONDUCTOR

- In semiconductors, the forbidden gap between valence band and conduction band is very small. It has a forbidden gap of about 1 electron volt (eV).
- At low temperature, the valence band is completely occupied with electrons and conduction band is empty because the electrons in the valence band does not have enough energy to move in to conduction band. Therefore, semiconductor behaves as an insulator at low temperature.
- However, at room temperature some of the electrons in valence band gains enough energy in the form of heat and moves in to conduction band. When the valence electrons moves in to conduction band they becomes free electrons. These electrons are not attached to the nucleus of a atom, So they moves freely.
- The conduction band electrons are responsible for electrical conductivity. The measure of ability to conduct electric current is called as electrical conductivity.

- When the temperature is goes on increasing, the number of valence band electrons moving in to conduction band is also increases. This shows that electrical conductivity of the semiconductor increases with increase in temperature. i.e. a semiconductor has negative temperature co-efficient of resistance. The resistance of semiconductor decreases with increase in temperature.
- In semiconductors, electric current is carried by two types of charge carriers they are electrons and holes.

2.2 CONCEPT OF HOLE :

- The absence of electron in a particular place in an atom is called as hole.
- Hole is a electric charge carrier which has positive charge. The electric charge of hole is equal to electric charge of electron but have opposite polarity.

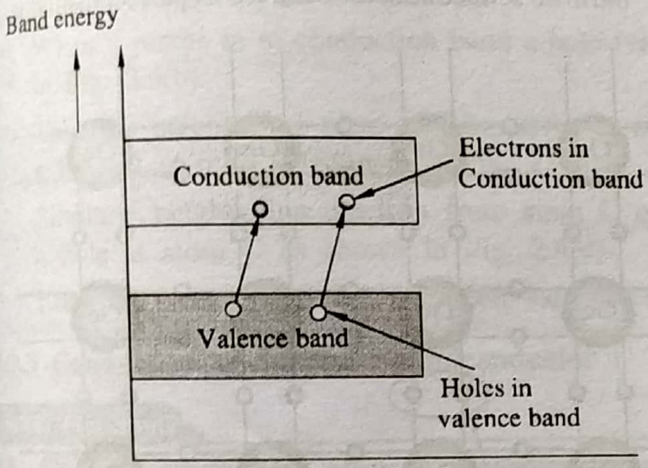


FIG. 2.2 : CONCEPT OF HOLE

- When a small amount of external energy is applied, then the electrons in the valence band moves in to conduction band and leaves a vacancy in valence band. This vacancy is called as hole.

Syllabus Topic : Intrinsinc Semiconductors

2.3 INTRINSIC SEMICONDUCTOR :

- Pure semiconductors are called intrinsic semiconductors.
- Silicon and germanium are the most common examples of intrinsic semiconductors.
- Both these semiconductors are most frequently used in the manufacturing of transistors, diodes and other electronic components.
- In intrinsic semiconductor, the number of electrons in the conduction band is equal to the number of holes in the valence band. Therefore the overall electric charge of a atom is neutral.

2.3.1 Atomic Structure of Silicon and Germanium :

- The atomic structure of intrinsic semiconductor materials like silicon and germanium is as follows.

1. Atomic structure of silicon :

- Silicon is a substance consisting of atoms which all have the same number of protons.
- The atomic number of silicon is 14 i.e. 14 protons.
- The number of protons in the nucleus of an atom is called atomic number.
- Silicon atom has 14 electrons (two electrons in first orbit, eight electrons in second orbit and 4 electrons in the outermost orbit).

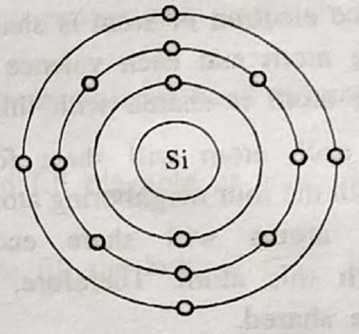


FIG. 2.3 : ATOMIC STRUCTURE OF SILICON

2. Atomic structure of germanium :

- Germanium is a substance consisting of atoms which all have the same number of protons.
- The atomic number of germanium is 32 i.e. 32 protons.
- The number of protons in the nucleus of atom is called atomic number.

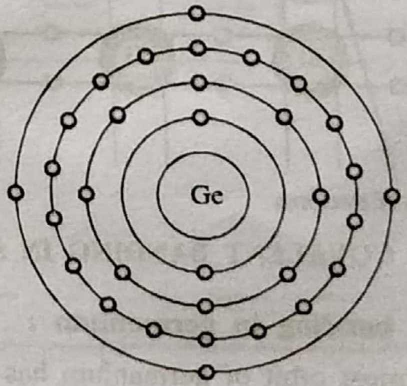


FIG. 2.4 : ATOMIC STRUCTURE OF GERMAINIUM

Scanned by CamScanner

- Germanium has 32 electrons (2 electrons in first orbit, 8 electrons in second orbit, 18 electrons in third orbit and 4 electrons in the outermost orbit.

3. **Covalent bonding in silicon :**

- The outermost shell of atom is capable to hold up to eight electrons. The atom which has eight electrons in the outermost orbit is said to be completely filled and most stable.
- But the outermost orbit of silicon has only four electrons. Silicon atom needs four more electrons to become most stable.
- Silicon atom forms four covalent bonds with the four neighboring atoms.
- In covalent bonding each valence electron is shared by two atoms.
- When silicon atoms comes close to each other, each valence electron of atom is shared with the neighboring atom and each valence electron of neighboring atom is shared with this atom.
- Likewise each atom will share four valence electrons with the four neighboring atoms and four neighboring atoms will share each valence electron with this atom. Therefore, total eight electrons are shared.

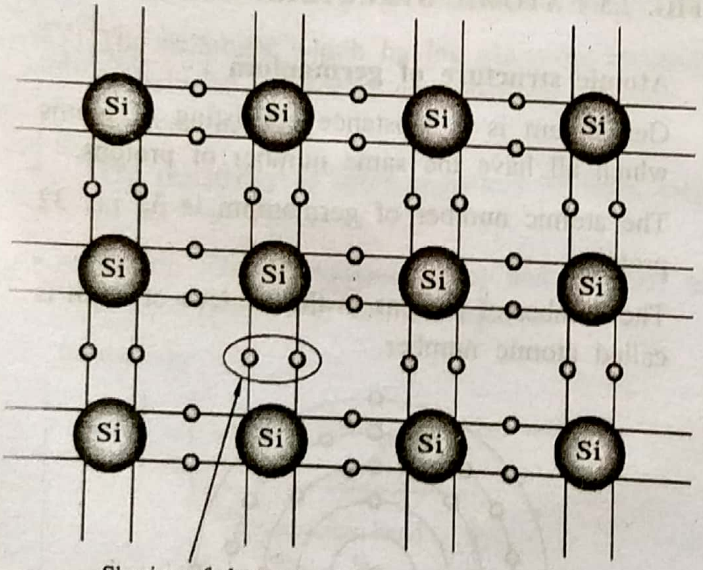


FIG. 2.5(a) : COVALENT BANDING IN SILICON

4. **Covalent bonding in germanium :**

- The outermost orbit of germanium has only four electrons. Germanium atom needs four more electrons to become most stable.
- Germanium atom forms four covalent bonds with the four neighboring atoms. In covalent bonding each valence electron is shared by two atoms.
- When germanium atoms comes close to each other each valence electron of atom is shared with the neighboring atom and each valence electron of neighboring atom is shared with this atom.
- Likewise each atom will share four valence electrons with the four neighboring atoms and four neighboring atoms will share each valence electron with this atom. Therefore, total eight electrons are shared.
- The outermost shell of silicon and germanium is completely filled and valence electrons are tightly bound to the nucleus of atom because of sharing electrons with neighboring atoms.
- In intrinsic semiconductors free electrons are not present at absolute zero temperature. Therefore intrinsic semiconductor behaves as perfect insulator.

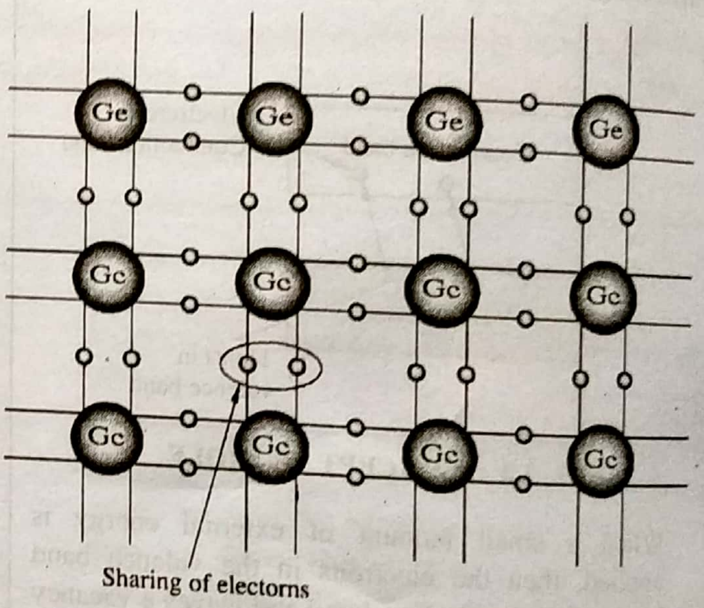


FIG. 2.5(b) : COVALENT BONDING IN GERMANIUM

2.3.2 Electron and Hole Current :

- In conductors, current is caused by only motion of electrons but in semiconductors, current is caused by both electrons in conduction band and holes in valence band.
- Current that is caused by electron motion is called electron current and current that is caused by hole motion is called hole current. Electron is a negative charge carrier whereas hole is a positive charge carrier.

- At absolute zero temperature intrinsic semiconductor behaves as insulator.
- However, at room temperature the electrons present in the outermost orbit absorb thermal energy.
- When the outermost orbit electrons get enough energy then they will break bonding with the nucleus of atom and jumps in to conduction band.

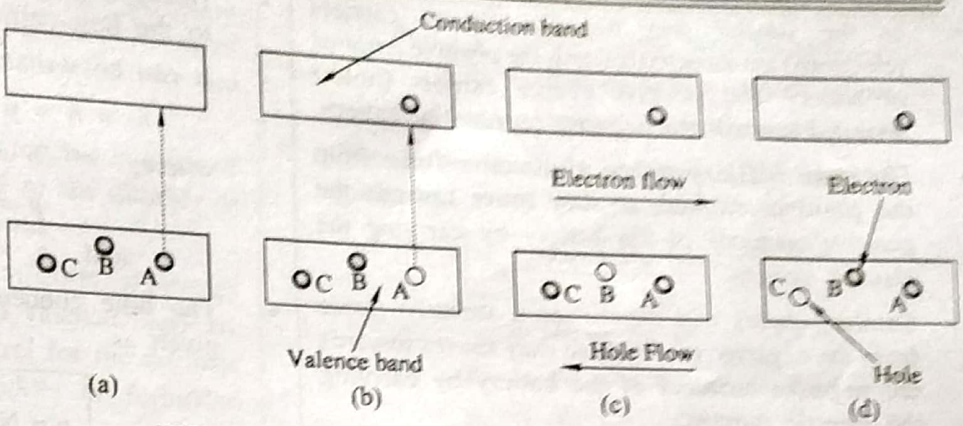


FIG. 2.6 : ELECTRON AND HOLE CURRENT

- The electrons present in conduction band are not attached to the nucleus of an atom so they are free to move.
- When the valence electron moves from valence band to the conduction band a vacancy is created in the valence band where electron left. Such vacancy is called hole.
- Let's take an example, as shown in Fig 2.6. there are three atoms atom A, atom B and atom C.
- At room temperature valence electron in an atom A gains enough energy and jumps in to conduction band as show in Fig. 2.6(a).
- When it jumps in to conduction band a hole (vacancy) is created in the valence band at atom A as shown in Fig. 2.6(b).
- Then the neighboring electron from atom B moves to atom A to fill the hole at atom A. This creates a hole at atom B as shown in Fig. 2.6(c).
- Similarly neighboring electron from atom C moves to atom B to fill the hole at atom B. This creates a hole at atom C as shown in Fig. 2.6(d).
- Likewise electrons moves from left side to right side and holes moves from right to left side.

2.3.3 Conduction in Intrinsic Semiconductor :

GTU, January-2019

GTU Questions

1. Derive expression of electron concentration in conduction band. **[January-2019, 4-Marks]**

- The process of conduction in intrinsic semiconductor is shown in Fig. 2.7.
- In the Fig 2.7, an intrinsic semiconductor is connected to a battery.
- Here, positive terminal of battery is connected to one side and negative terminal of the battery is connected to other side.
- As we know like charges repel each other and opposite charges attract each other.

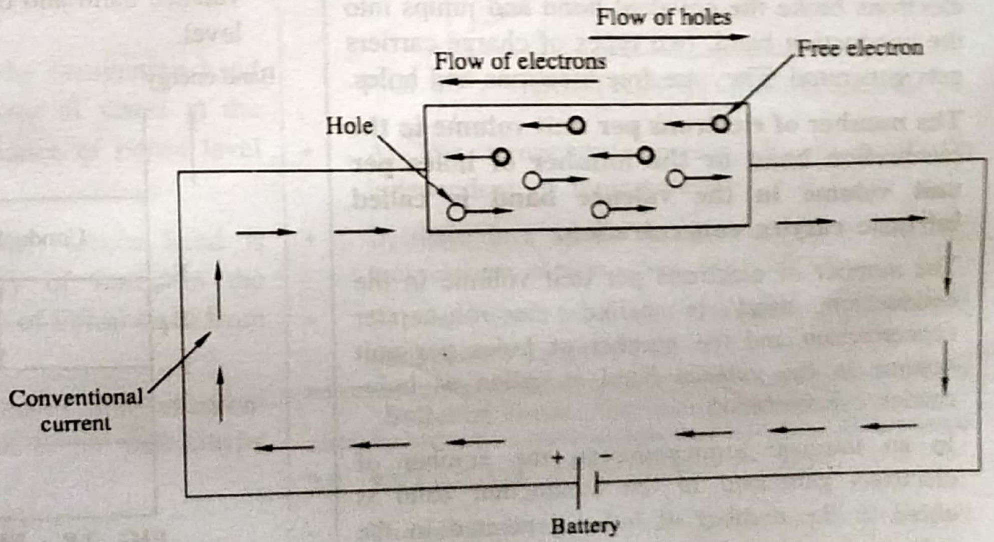


FIG. 2.7 : CONDUCTION IN INTRINSIC SEMICONDUCTOR

- In the similar way negative charge carriers (electrons) are attracted towards the positive terminal of battery and positive charge carriers (holes) attracted towards the negative terminal of battery.
- Electrons will experience a attractive force from the positive terminal, so they move towards the positive terminal of the battery by carrying the electric current.
- Similarly holes will experience a attractive force from the negative terminal, so they moves towards the negative terminal of the battery by carrying the electric current.
- Thus, in a semiconductor electric current is carried by both electrons and holes.
- In intrinsic semiconductor the number of free electrons in conduction band is equal to the number of holes in valence band.
- The current caused by electrons and holes is equal in magnitude.
- The total current in intrinsic semiconductor is the sum of hole and electron current.
- Total current = Electron current + Hole current

$$\boxed{I = I_{hole} + I_{electron}}$$

2.3.4 Intrinsic Carrier Concentration :

GTU, January-2019

GTU Questions

1. Derive expression of electron concentration in conduction band. **[January-2019, 4-Marks]**

- In intrinsic semiconductor, when the valence electrons broke the covalent bond and jumps into the conduction band, two types of charge carriers gets generated. They are free electrons and holes.
- **The number of electrons per unit volume in the conduction band or the number of holes per unit volume in the valence band is called intrinsic carrier concentration.**
- The number of electrons per unit volume in the conduction band is called electron-carrier concentration and the number of holes per unit volume in the valence band is called as hole-carrier concentration.
- In an intrinsic semiconductor, the number of electrons generated in the conduction band is equal to the number of holes generated in the valence band.
- Hence the electron-carrier concentration is equal to the hole-carrier concentration.
- It can be written as,

$$n_i = n = p$$

where, n = electron-carrier concentration

p = hole-carrier concentration

and n_i = intrinsic carrier concentration

- The hole concentration in the valence band is given as

$$\boxed{p = N_v\, e^{\frac{-(E_F - E_V)}{K_B T}}}$$

- The electron concentration in the conduction band is given as

$$\boxed{n = N_c\, e^{\frac{-(E_C - E_F)}{K_B T}}}$$

where, K_B = the Boltzmann constant

T = the absolute temperature of intrinsic semiconductor

N_c = the effective density of states in conduction band.

N_v = the effective density of states in valence band.

Syllabus Topic : Dependence of Fermi level on carrier-concentration and temperature

2.4 FERMI LEVEL IN INTRINSIC SEMICONDUCTOR :

- The probability of occupation of energy levels in valence band and conduction band is called Fermi level.

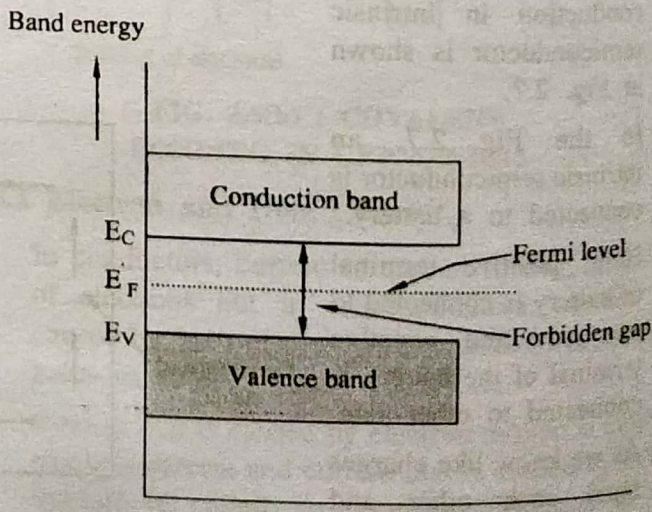


FIG. 2.8 : FERMI LEVEL IN INTRINSIC SEMICONDUCTOR

- At absolute zero temperature intrinsic semiconductor acts as perfect insulator. However as the temperature increases free electrons and holes gets generated.
- In intrinsic or pure semiconductor, the number of holes in valence band is equal to the number of electrons in the conduction band.
- Hence, the probability of occupation of energy levels in conduction band and valence band are equal. Therefore, the Fermi level for the intrinsic semiconductor lies in the middle of forbidden band.
- Fermi level in the middle of forbidden band indicates equal concentration of free electrons and holes.
- The hole-concentration in the valence band is given as

$$\boxed{p = N_v e^{\frac{-(E_F - E_V)}{K_B T}}}$$

- The electron-concentration in the conduction band is given as

$$\boxed{n = N_c e^{\frac{-(E_C - E_F)}{K_B T}}}$$

where, K_B = the Boltzmann constant

T = the absolute temperature of the intrinsic semiconductor

N_c = the effective density of states in the conduction band.

N_v = the effective density of states in the valence band.

- The number of electrons in the conduction band is depends on effective density of states in the conduction band and the distance of Fermi level from the conduction band.
- The number of holes in the valence band is depends on effective density of states in the valence band and the distance of Fermi level from the valence band.
- For an intrinsic semiconductor, the electron-carrier concentration is equal to the hole-carrier concentration.
- It can be written as

$$\boxed{p = n = n_i}$$

where, p = hole-carrier concentration

n = electron-carrier concentration

and n_i = intrinsic carrier concentration

- The fermi level for intrinsic semiconductor is given as,

$$\boxed{E_F = \frac{E_C + E_V}{2}}$$

where, E_F is the fermi level

E_C is the conduction band

E_V is the valence band

- Therefore, the Fermi level in an intrinsic semiconductor lies in the middle of the forbidden gap.

2.4.1 Dependence of E_F on Temperature :

- The variation of Fermi level with temperature for an intrinsic semiconductor is shown in Fig. 2.9.
- At T = 0 K, the Fermi level lies exactly in middle of forbidden gap as shown in Fig. 2.9(a).

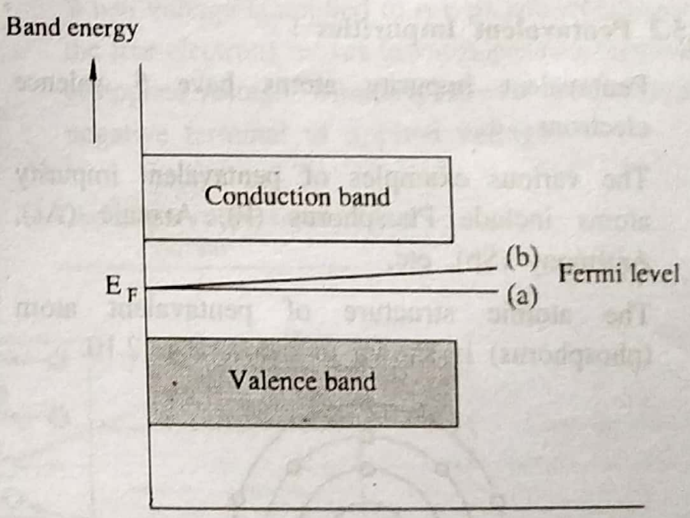


FIG. 2.9 : VARIATION OF FERMI LEVEL

- At low temperature region, E_F is practically independent of temperature.
- If, there is a small variation in E_F in the high temperature region. (See Fig. 2.9(b))
- So, the Fermi level gets increased slightly when temperature is increased.

Syllabus Topic : Extrinsic Semiconductors

2.5 EXTRINSIC SEMICONDUCTOR :

- The semiconductor in which impurities are added is called extrinsic semiconductor.

- When the impurities are added to the intrinsic semiconductor, it becomes an extrinsic semiconductor.
- The process of adding impurities to the semiconductor is called doping.
- Doping increases the electrical conductivity of semiconductor.
- Extrinsic semiconductor has high electrical conductivity than intrinsic semiconductor.
- Hence the extrinsic semiconductors are used for the manufacturing of electronic devices such as diodes, transistors etc.
- The number of free electrons and holes in extrinsic semiconductor are not equal.

2.5.1 Types of Impurities :

- Two types of impurities are added to the semiconductor.
- They are pentavalent and trivalent impurities.

2.5.2 Pentavalent Impurities :

- Pentavalent impurity atoms have 5 valence electrons.
- The various examples of pentavalent impurity atoms include Phosphorus (P), Arsenic (As), Antimony (Sb), etc.
- The atomic structure of pentavalent atom (phosphorus) is shown in below Fig. 2.10.

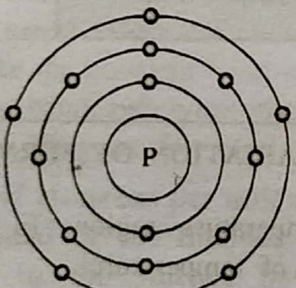


FIG. 2.10 : PENTAVALENT ATOM (PHOSPHORUS)

- Phosphorus is a substance consisting of atoms which all have the same number of protons.
- The atomic number of phosphorus is 15 i.e. 15 protons. The number of protons in the nucleus of an atom is called atomic number.
- Phosphorus atom has 15 electrons (2 electrons in first orbit, 8 electrons in second orbit and 5 electrons in the outermost orbit).

2.5.3 Trivalent Impurities :

- Trivalent impurity atoms have 3 valence electrons.
- The various examples of trivalent impurities include Boron (B), Gallium (G), Indium (In), Aluminium (Al).
- Boron is a substance consisting of atoms which all have the same number of protons. The atomic number of boron is 5 i.e. 5 protons.
- Boron atom has 5 electrons (2 electrons in first orbit and 3 electrons in the outermost orbit).

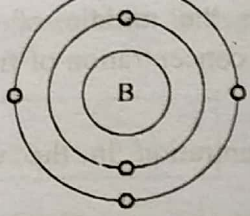


FIG. 2.11 : TRIVALENT ATOM (BORON)

2.5.4 Classification of Extrinsic Semiconductors Based on Impurities Added :

- Based on the type of impurities added, extrinsic semiconductors are classified in to two types.

1. N-type Semiconductor
2. P-type Semiconductor

1. N-type Semiconductor :

- When pentavalent impurity is added to an intrinsic or pure semiconductor (silicon or germanium), then it is said to be an n-type semiconductor.
- Pentavalent impurities such as phosphorus, arsenic, antimony etc. are called donor impurity.
- Let us consider, pentavalent impurity phosphorus is added to silicon as shown in below figure.
- Phosphorus atom has 5 valence electrons and silicon has 4 valence electrons.
- Phosphorus atom has one excess valence electron than silicon. The four valence electrons of each phosphorus atom form 4 covalent bonds with the 4 neighboring silicon atoms.
- The fifth valence electron of the phosphorus atom cannot able to form the covalent bond with the silicon atom because silicon atom does not have the fifth valence electron to form the covalent bond.

- Thus, fifth valence electron of phosphorus atom does not involve in the formation of covalent bonds. Hence, it is free to move and not attached to the parent atom.

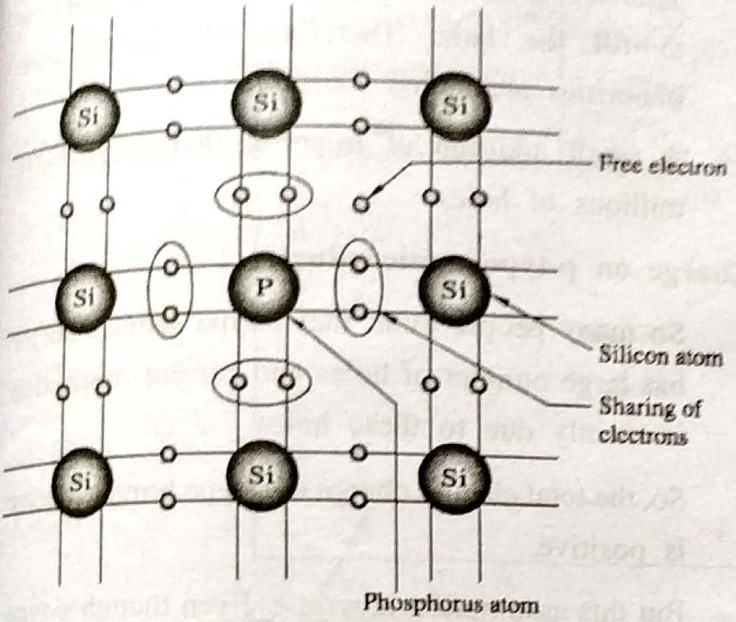


FIG. 2.12 : N-TYPE SEMICONDUCTOR

- This shows that each phosphorus atom donates one free electron.
- Therefore, all the pentavalent impurities are called donors.
- The number of free electrons are depends on the amount of impurity (phosphorus) added to the silicon.
- A small addition of impurity (phosphorus) generates millions of free electrons.

Charge on n-type semiconductor :

- So many people think that n-type semiconductor has large number of free electrons. So, the total electric charge of n-type semiconductor is negative. But this assumption is wrong.
- Even though n-type semiconductor has large number of free electrons, but these free electrons is given by the pentavalent atoms that are electrically neutral. Therefore, the total electric charge of n-type semiconductor is also neutral.

Conduction in n-type semiconductor :

- Let us consider an n-type semiconductor as shown in below figure.
- When voltage is applied to n-type semiconductor, the free electrons moves towards positive terminal of applied voltage. Similarly holes moves towards negative terminal of applied voltage.

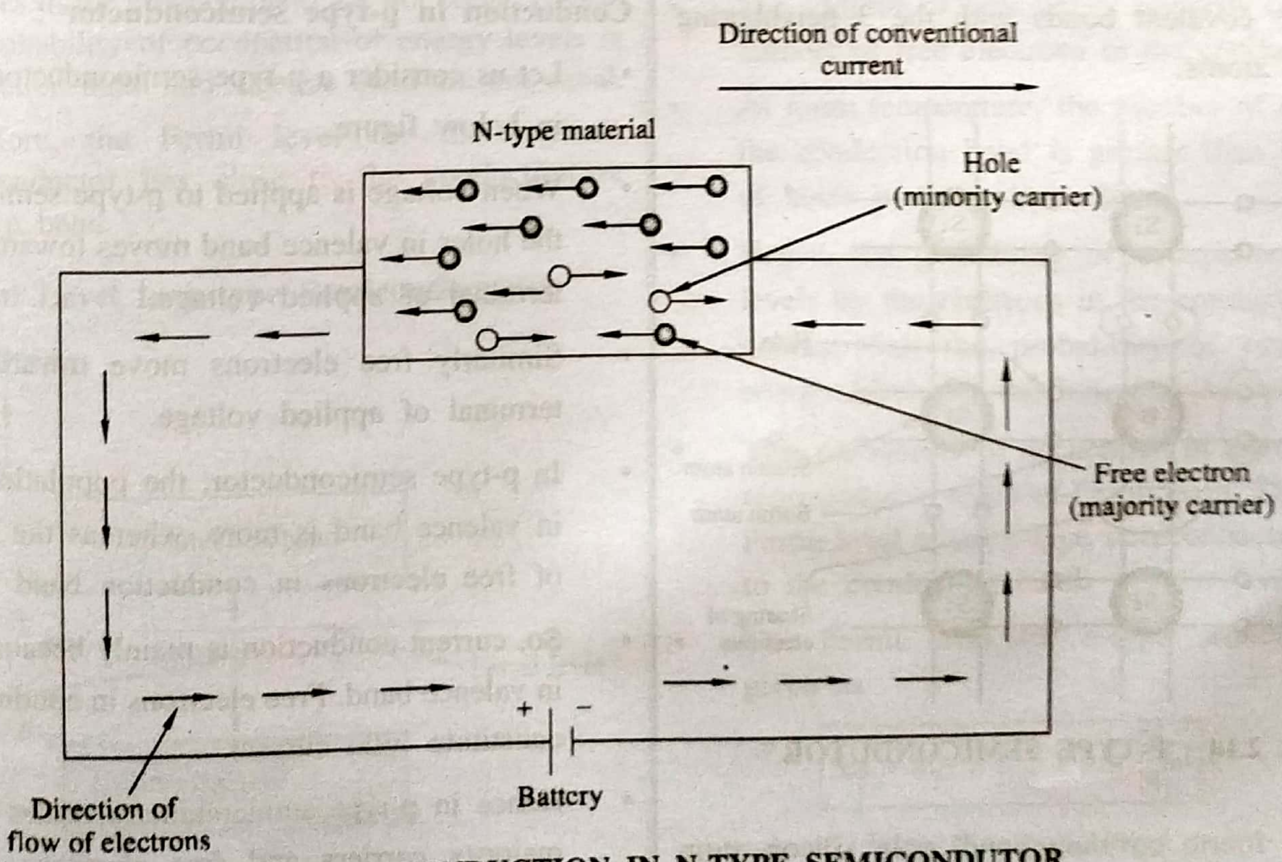


FIG. 2.13 : CONDUCTION IN N-TYPE SEMICONDUTOR

- In n-type semiconductor, the population of free electrons is more whereas the population of holes is less.
- Hence in n-type semiconductor free electrons are called majority carriers and holes are called minority carriers.
- Therefore, in a n-type semiconductor conduction is mainly because of motion of free electrons.

2. P-type Semiconductor :

- When the trivalent impurity is added to an intrinsic or pure semiconductor (silicon or germanium), then it is said to be an p-type semiconductor.
- Trivalent impurities such as Boron (B), Gallium (G), Indium (In), Aluminium (Al) etc are called acceptor impurity.
- Let us consider, trivalent impurity boron is added to silicon as shown in below figure. Boron atom has three valence electrons and silicon has four valence electrons.
- The three valence electrons of each boron atom form 3 covalent bonds with the 3 neighboring silicon atoms.

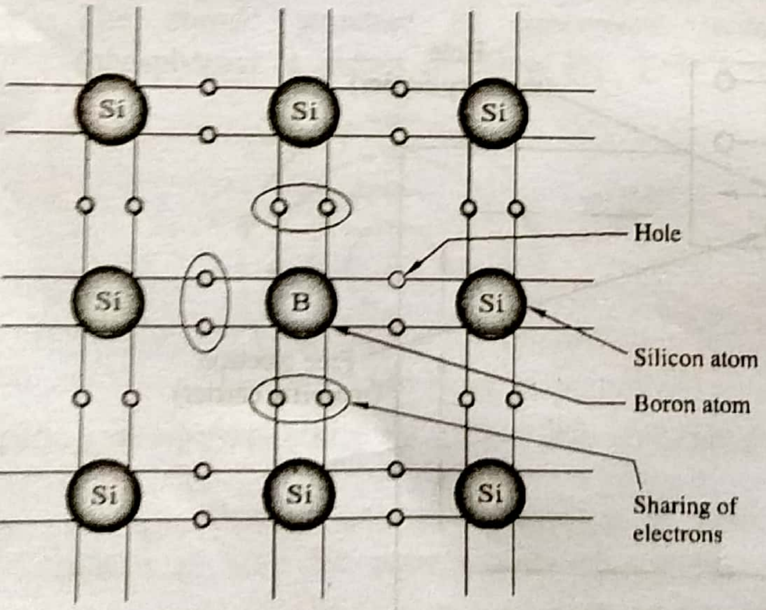


FIG. 2.14 : P-TYPE SEMICONDUTOR

In the fourth covalent bond, only silicon atom contributes one valence electron, while the boron atom has no valence electron to contribute.

- Thus, the fourth covalent bond is incomplete with shortage of one electron. This missing electron is called hole.
- This shows each boron atom accept one electron to fill the hole. Therefore, all the trivalent impurities are called acceptors.
- A small addition of impurity (boron) provides millions of holes.

Charge on p-type semiconductor :

- So many people think that p-type semiconductor has large number of holes and current conduction is mainly due to these holes.
- So, the total electric charge of p-type semiconductor is positive.
- But this assumption is wrong. Even though p-type semiconductor has large number of holes, but these holes is provided by the trivalent atoms that are electrically neutral.
- Therefore, the total electric charge of p-type semiconductor is also neutral.

Conduction in p-type semiconductor :

- Let us consider a p-type semiconductor as shown in below figure.
- When voltage is applied to p-type semiconductor, the holes in valence band moves towards negative terminal of applied voltage.
- Similarly free electrons move towards positive terminal of applied voltage.
- In p-type semiconductor, the population of holes in valence band is more, whereas the population of free electrons in conduction band is less.
- So, current conduction is mainly because of holes in valence band. Free electrons in conduction band constitute little current.
- Hence in p-type semiconductor, holes are called majority carriers and free electrons are called minority carriers.

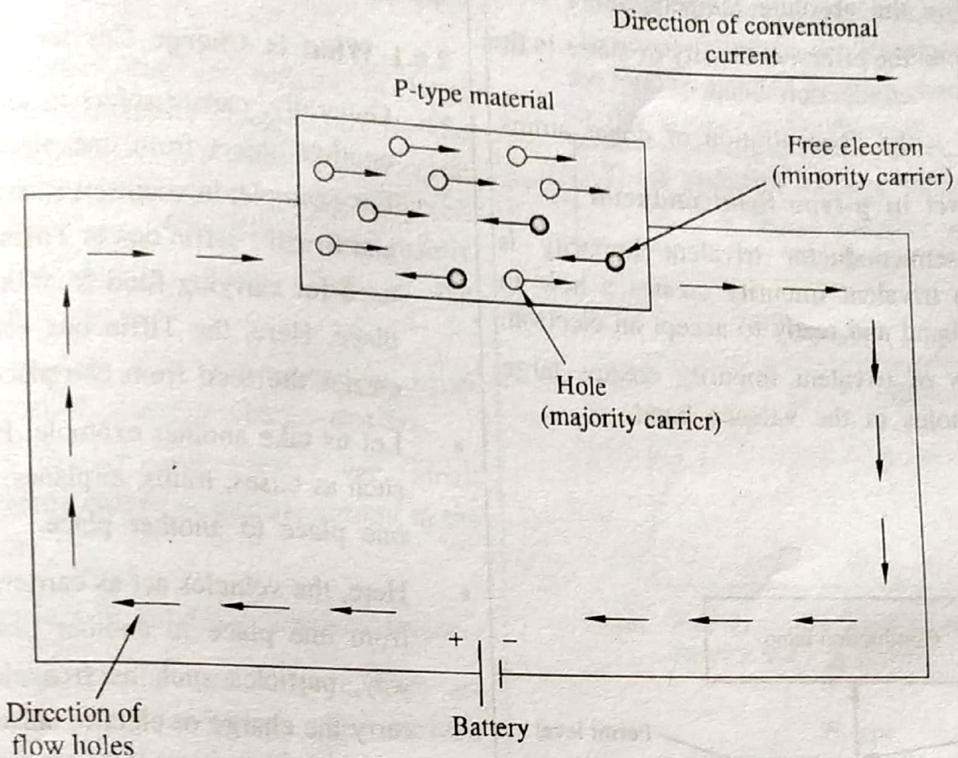


FIG. 2.15 : CONDUCTIN IN P-TYPE SEMICONDUTOR

2.5.5 Fermi Level in Extrinsic Semiconductor :

- In extrinsic semiconductor, the number of electrons in the conduction band and the number of holes in the valence band are not equal. Hence, the probability of occupation of energy levels in conduction band and valence band are not equal.
- Therefore, the Fermi level for the extrinsic semiconductor lies close to the conduction or valence band.

2.5.6 Fermi Level in n-type Semiconductor :

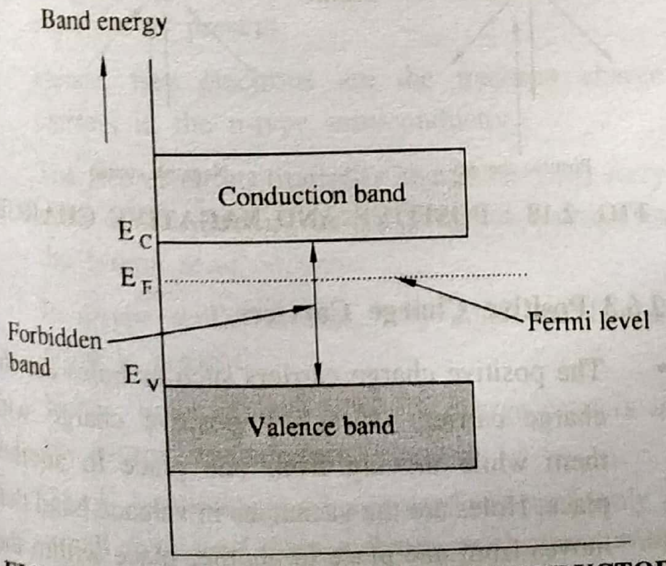


FIG. 2.16 : FERMI IN N-TYPE SEMICONDUCTOR

- In n-type semiconductor pentavalent impurity is added. Each pentavalent impurity donates a free electron.
- The addition of pentavalent impurity creates large number of free electrons in the conduction band.
- At room temperature, the number of electrons in the conduction band is greater than the number of holes in the valence band.
- Hence, the probability of occupation of energy levels by the electrons in the conduction band is greater than the probability of occupation of energy levels by the holes in the valence band.
- This probability of occupation of energy levels is represented in terms of Fermi level. Therefore, the Fermi level in the n-type semiconductor lies close to the conduction band.
- The Fermi level for n-type semiconductor is given as

$$\boxed{E_F = E_C + K_B\, T \log \frac{N_C}{N_D}}$$

where, E_F = the fermi level.

E_C = the conduction band.

K_B = the Boltzmann constant.

T = the absolute temperature.

N_C = the effective density of states in the conduction band.

N_D = the concentration of donar atoms.

2.5.7 Fermi Level in p-type Semiconductor :

- In p-type semiconductor trivalent impurity is added. Each trivalent impurity creates a hole in the valence band and ready to accept an electron.
- The addition of trivalent impurity creates large number of holes in the valence band.

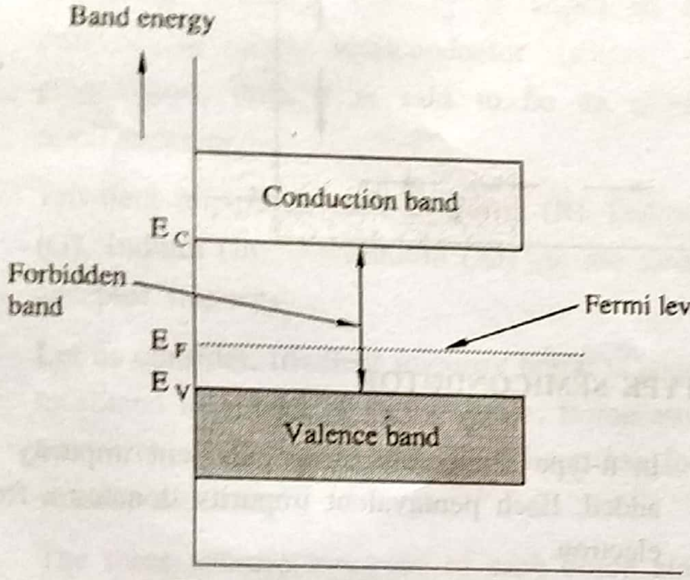


FIG. 2.17 : FERMI LEVEL IN P-TYPE SEMICONDUCTOR

- At room temperature, the number of holes in the valence band is greater than the number of electrons in the conduction band.
- Hence, the probability of occupation of energy levels by the holes in the valence band is greater than the probability of occupation of energy levels by the electrons in the conduction band. This probability of occupation of energy levels is represented in terms of Fermi level.
- Therefore, the Fermi level in the p-type semiconductor lies close to the valence band.
- The Fermi level for p-type semiconductor is given as

$$\boxed{E_F = E_V + K_B T \log \frac{N_V}{N_A}}$$

where, N_V = the effective density of states in the valence band.

N_A = the concentration of acceptor atoms.

2.6 MAJORITY AND MINORITY CARRIERS :

2.6.1 What is Charge Carrier ?

- Generally, carrier refers to any object that carry another object from one place to another place. For example, in countries such as India, Singapore and Brazil : Tiffin box or Tiffin carriers are widely used for carrying food from one place to another place. Here, the Tiffin box acts as a carrier that carries the food from one place to another place.
- Let us take another example; People use vehicles such as buses, trains, airplanes, etc. to travel from one place to another place.
- Here, the vehicles act as carriers that carry people from one place to another place. In the similar way, particles such as free electrons and holes carry the charge or electric current from one place to another place.

2.6.2 Negative Charge Carriers :

- The negative charge carriers such as free electrons are the charge carriers that carry negative charge with them while moving from one place to another place. Free electrons are the electrons that are detached from the parent atom and moves freely from one place to another place.

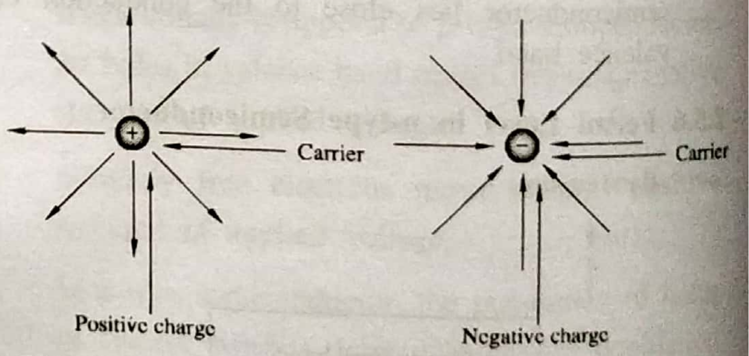


FIG. 2.18 : POSITIVE AND NAGATIVE CHARGE

2.6.3 Positive Charge Carriers :

- The positive charge carriers such as holes are the charge carriers that carry positive charge with them while moving from one place to another place. Holes are the vacancies in valence band that moves from one place to another place within the valence band.

2.6.4 Majority and Minority Charge Carriers Definition :

- The charge carriers that are present in large quantity are called majority charge carriers. The majority charge carriers carry most of the electric charge or electric current in the semiconductor. Hence, majority charge carriers are mainly responsible for electric current flow in the semiconductor.
- The charge carriers that are present in small quantity are called minority charge carriers.
- The minority charge carriers carry very small amount of electric charge or electric current in the semiconductor.

2.6.5 Charge Carriers in Intrinsic Semiconductor :

- The semiconductors that are in pure form are called intrinsic semiconductors. In intrinsic semiconductor the total number of negative charge carriers (free electrons) is equal to the total number of positive charge carriers (holes or vacancy).

Total negative charge carriers **= Total positive charge carriers**

2.6.6 Majority and Minority Charge Carriers in n-Type Semiconductor :

- When the pentavalent atoms such as Phosphorus or Arsenic are added to the intrinsic semiconductor, an n-type semiconductor is formed.
- In n-type semiconductor, large number of free electrons is present.
- Hence, free electrons are the majority charge carriers in the n-type semiconductor.
- The free electrons (majority charge carriers) carry most of the electric charge or electric current in the n-type semiconductor.
- In n-type semiconductor, very small number of holes is present.
- Hence, holes are the minority charge carriers in the n-type semiconductor.
- The holes (minority charge carriers) carry only a small amount of electric charge or electric current in the n-type semiconductor.
- *The total number of negative charge carriers (free electrons) in n-type semiconductor is greater than the total number of positive charge carriers (holes) in the n-type semiconductor.*

Total negative charge carriers **> Total positive charge carriers**

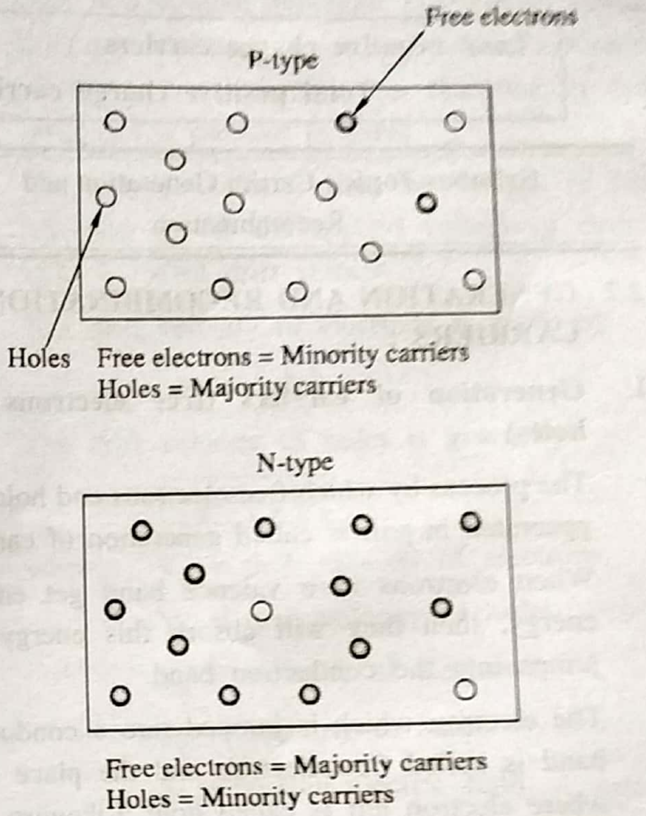


FIG. 2.19 : MAJORITY AND MINORITY CHARGE CARRIERS IN P-TYPE AND N-TYPE SEMICONDUCTOR

2.6.7 Majority and minority charge carriers in p-type semiconductor :

- When the trivalent atoms such as Boron or Gallium are added to the intrinsic semiconductor, a p-type semiconductor is formed.
- In p-type semiconductor, large number of holes is present. Hence, holes are the majority charge carriers in the p-type semiconductor.
- The holes (majority charge carriers) carry most of the electric charge or electric current in the p-type semiconductor.
- In p-type semiconductor, very small number of free electrons is present. Hence, free electrons are the minority charge carriers in the p-type semiconductor.

- The free electrons (minority charge carriers) carry only a small amount of electric current in the p-type semiconductor.
- The total number of negative charge carriers (free electrons) in p-type semiconductor is less than the total number of positive charge carriers (holes) in the p-type semiconductor.

Total negative charge carriers
< Total positive charge carriers

Syllabus Topic : Carrier Generation and Recombination

2.7 GENERATION AND RECOMBINATION OF CARRIERS :

1. **Generation of carriers (free electrons and holes) :**

- The process by which free electrons and holes are generated in pair is called generation of carriers.
- When electrons in a valence band get enough energy, then they will absorb this energy and jumps into the conduction band.
- The electron which is jumped into a conduction band is called free electron and the place from where electron left is called hole. Likewise, two type of charge carriers (free electrons and holes) gets generated.

2. **Recombination of carriers (free electrons and holes) :**

- The process by which free electrons and the holes get eliminated is called recombination of carriers.
- When free electron in the conduction band falls in to a hole in the valence band, then the free electron and hole gets eliminated.

2.8 LAW OF MASS ACTION :

- The law of mass action states that the product of number of electrons in the conduction band and the number of holes in the valence band is constant at a fixed temperature and is independent of amount of donor and acceptor impurity added.
- Mathematically it is represented as

$$\boxed{n\,p = n_i^2 = \text{constant}}$$

where, n_i = is the intrinsic carrier concentration

n = number of electrons in conduction band

p = number of holes in valence band

2.8.1 Law of Mass Action for Extrinsic Semiconductor :

- The law of mass action is applied for both intrinsic and extrinsic semiconductors. For extrinsic semiconductor the law of mass action states that the product of majority carriers and minority carriers is constant at fixed temperature and is independent of amount of donor and acceptor impurity added.

1. **Law of mass action for n-type semiconductor :**

- The law of mass action for n-type semiconductor is mathematically written as

$$\boxed{n_n\, p_n = n_i^2 = \text{constant}}$$

where, n_n = number of electrons in n-type semiconductor

p_n = number of holes in n-type semiconductor

- The electrons are the majority carriers and holes are the minority carriers in n-type semiconductor.
- In n-type semiconductor, as the number of electrons (majority) in the conduction band increases the number of holes (minority) in the valence band decreases.
- Therefore, the product of electrons (majority) and holes (minority) remains constant at fixed temperature.

2. **Law of mass action for p-type semiconductor :**

- The law of mass action for p-type semiconductor is mathematically written as

$$\boxed{p_p\, n_p = n_i^2 = \text{constant}}$$

where, p_p = number of holes in p-type semiconductor

n_p = number of electrons in p-type semiconductor

- The holes are the majority carriers and electrons are the minority carriers in p-type semiconductor.

- In p-type semiconductor, as the number of holes (majority) in the valence band increases the number of electrons in the conduction band (minority) decreases.
- Therefore, the product of holes (majority) and electrons (minority) remains constant at fixed temperature.

Syllabus Topic : Drift

2.9 DRIFT CURRENT : **GTU, January-2019**

GTU Questions

1. Explain drift and diffusion current. **[January-2019, 4-Marks]**

- The flow of charge carriers, which is due to the applied voltage or electric field is called drift current.
- In a semiconductor, there are two types of charge carriers, they are electrons and holes.
- When the voltage is applied to a semiconductor, the free electrons move towards the positive terminal of a battery and holes move towards the negative terminal of a battery.
- Electrons are the negatively charged particles and holes are the positively charged particles.
- As we already discussed that like charges repel each other and unlike charges attract each other.
- Hence, the electrons (negatively charged particle) are attracted towards the positive terminal of a battery and holes (positively charged particle) are attracted towards the negative terminal.

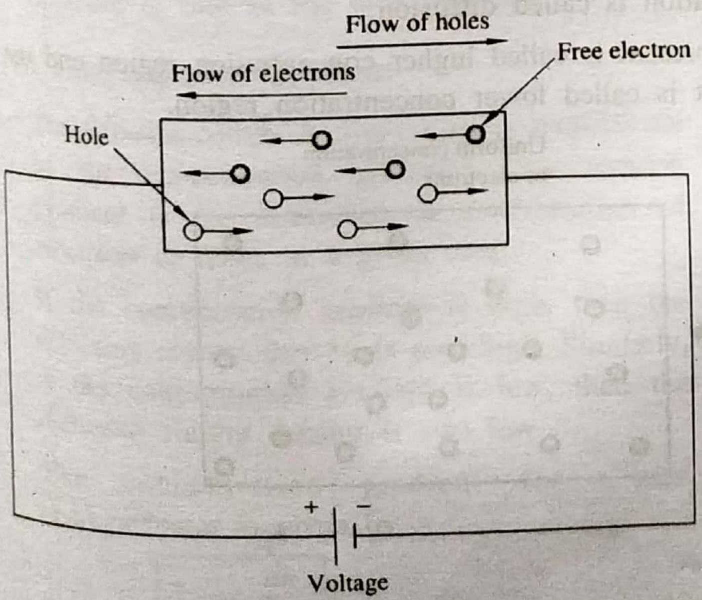


FIG. 2.20 : DRIFT CURRENT

- In a semiconductor, the electrons always try to move in a straight line towards the positive terminal of the battery. But, due to continuous collision with the atoms they change the direction of flow.
- Each time the electron strikes an atom it bounces back in a random direction. The applied voltage does not stop the collision and random motion of electrons, but it causes the electrons to drift towards the positive terminal.
- The average velocity that an electron or hole achieved due to the applied voltage or electric field is called drift velocity.
- The drift velocity of electrons is given by

$$\boxed{V_n = \mu_n E}$$

- The drift velocity of holes is given by

$$\boxed{V_p = \mu_p E}$$

where, V_n = drift velocity of electrons

V_p = drift velocity of holes

μ_n = mobility of electrons

μ_p = mobility of holes

E = applied electric field

- The drift current density due to free electrons is given by

$$\boxed{J_n = en\mu_n E}$$

and the drift current density due to holes is given by

$$\boxed{J_p = ep\mu_p E}$$

where, J_n = drift current density due to electrons

J_p = drift current density due to holes

e = charge of an electron = 1.602×10^{-19} Coulombs (C).

n = number of electrons

p = number of holes

- Then the total drift current density is

$$J = J_n + J_p$$

$$= en\mu_n E + ep\mu_p E$$

$$\boxed{J = e(n\mu_n + p\mu_p)E}$$

2.10 ELECTRON AND HOLE MOBILITY :

1. Electron mobility :

- The ability of an electron to move through a metal or semiconductor, in the presence of applied electric field is called electron mobility.
- It is mathematically written as

$$V_n = \mu_n E$$

$$\therefore \quad \boxed{\mu_n = \frac{V_n}{E}}$$

where, V_n = drift velocity of electrons
μ_n = mobility of electrons
E = applied electric field

- Let us consider a semiconductor that consists of large number of free electrons. When there is no voltage or electric field applied across the semiconductor, the free electrons moves randomly.
- However, when the voltage or electric field is applied across the semiconductor, each free electron starts to move more quickly in particular direction.
- Electrons move very fast in vacuum. However, in metals or semiconductors, free electrons do not move very fast instead they move with a finite average velocity, called drift velocity.
- Drift velocity is directly proportional to electric field. Hence, when the electric field increases drift velocity also increases.
- However, mobility of electrons is independent of applied electric field i.e. change in electric field does not change the mobility of electrons.
- The SI unit of electric field is V/m, and the SI unit of velocity is m/s. Thus, the SI unit of mobility is $m^2/(V.s)$.

2. Hole mobility :

- The ability of an hole to move through a metal or semiconductor, in the presence of applied electric field is called hole mobility.
- It is mathematically written as

$$V_p = \mu_p E$$

$$\therefore \quad \boxed{\mu_p = \frac{V_p}{E}}$$

where, V_p = drift velocity of holes
μ_p = mobility of holes
E = applied electric field

Syllabus Topic : Diffusion

2.11 DIFFUSION CURRENT :

GTU, January-2019

GTU Questions

1. Explain drift and diffusion current.

[January-2019, 4-Marks]

- The process by which, charge carriers (electrons or holes) in a semiconductor moves from a region of higher concentration to a region of lower concentration is called diffusion.
- The region in which more number of electrons is present is called higher concentration region and the region in which less number of electrons is present is called lower concentration region.

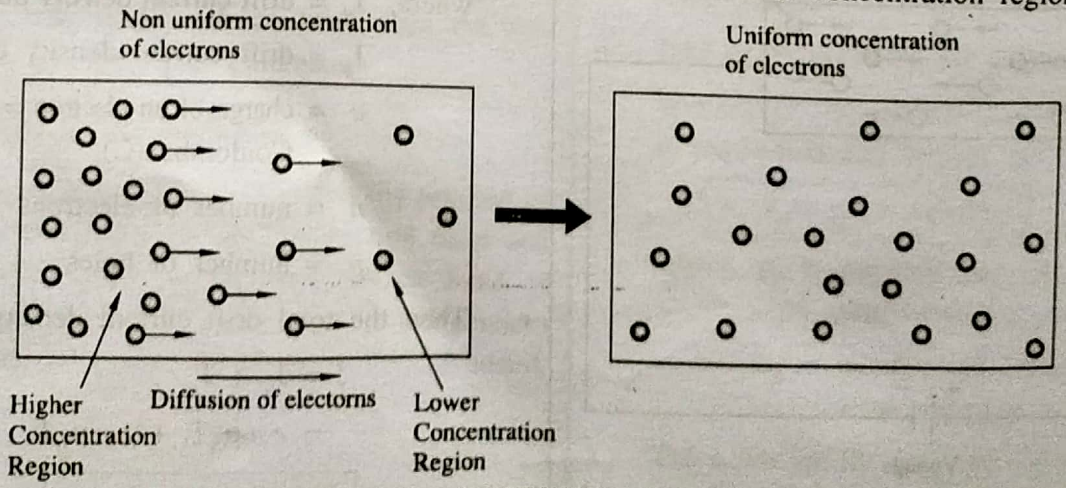


FIG. 2.21 : DIFFUSION CURRENT

- Current produced due to motion of charge carriers from a region of higher concentration to a region of lower concentration is called diffusion current. Diffusion process occurs in a semiconductor that is non-uniformly doped.
- Consider an n-type semiconductor that is non-uniformly doped as shown in below figure. Due to the non-uniform doping, more number of electrons is present at left side whereas lesser number of electrons is present at right side of the semiconductor material.
- The number of electrons present at left side of semiconductor material is more. So, these electrons will experience a repulsive force from each other.
- The electrons present at left side of the semiconductor material will moves to right side, to reach the uniform concentration of electrons.
- Thus, the semiconductor material achieves equal concentration of electrons. Electrons that moves from left side to right side will constitute current.
- This current is called diffusion current. In p-type semiconductor, the diffusion process occurs in the similar manner.
- Both drift and diffusion current occurs in semiconductor devices. Diffusion current occurs without an external voltage or electric field applied. Diffusion current does not occur in a conductor.
- The direction of diffusion current is same or opposite to that of the drift current.

2.11.1 Concentration Gradient :

- The diffusion current density is directly proportional to the concentration gradient. Concentration gradient is the difference in concentration of electrons or holes in a given area.
- If the concentration gradient is high, then the diffusion current density is also high. Similarly, if the concentration gradient is low, then the diffusion current density is also low.
- The concentration gradient for n-type semiconductor is given by

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

- The concentration gradient for p-type semiconductor is given by

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

where, J_n = diffusion current density due to electrons

J_p = diffusion current density due to holes

2.11.2 Diffusion Current Density :

- The diffusion current density due to electrons is given by

$$\boxed{J_n = + e D_n \frac{dn}{dx}}$$

where, D_n is the diffusion coefficient of electrons

- The diffusion current density due to holes is given by

$$\boxed{J_p = - e D_p \frac{dp}{dx}}$$

where, D_p is the diffusion coefficient of holes

- The total current density due to electrons is the sum of drift and diffusion currents.

J_n = Drift current + Diffusion current

$$\boxed{J_n = e n \mu_n E + e D_n \frac{dn}{dx}}$$

- The total current density due to holes is the sum of drift and diffusion currents.

J_p = Drift current + Diffusion current

$$\boxed{J_p = e n \mu_p E - e D_p \frac{dp}{dx}}$$

- The total current density due to electrons and holes is given by

$$\boxed{J = J_n + J_p}$$

Syllabus Topic : P-N Junction

2.12 THE P-N JUNCTION :

- When one-half of a crystal is a P-type semiconductor and the other half is an N-type semiconductor, the contact surface is called a PN junction.
- Most semiconductor devices contain one or more PN junctions.

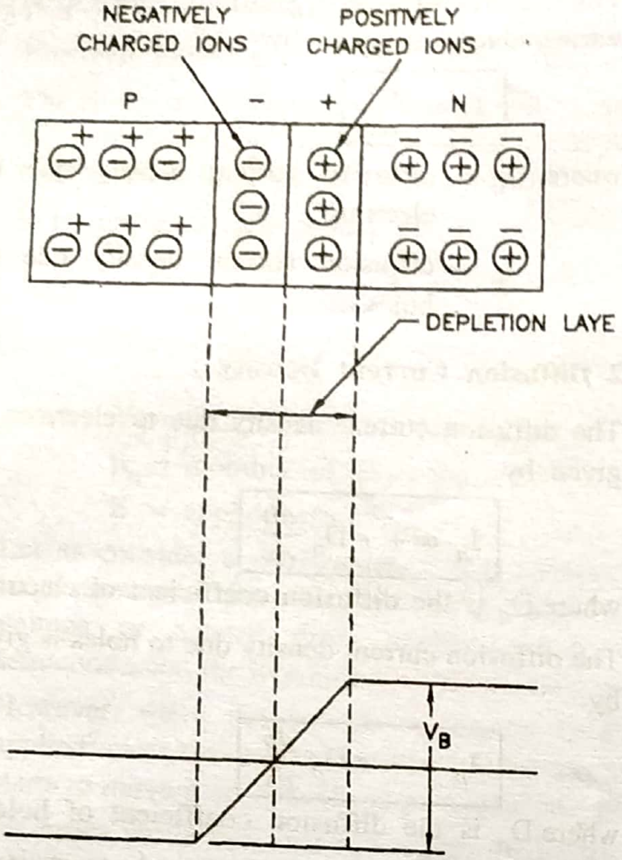


FIG. 2.22 : FORMATION OF PN-JUNCTION

- The PN junction is very important because it is the main control element in semiconductor devices.
- As mentioned earlier, an N-type semiconductor has free electrons and an equal number of stationary positive ions.
- While P-type semiconductor has mobile holes and an equal number of fixed negative ions. Thus each region in a PN junction is initially neutral.
- However, owing to their random motion, at the junction there is a tendency for the free electrons to diffuse over to the P-side and holes to the N-side.
- This process is called diffusion. As the free electrons move across the junction from N-type to p-type, the donor ions become positively charged.

Hence a positive charge is built on the N-side of the junction.

The free electrons that cross the junction uncover the negative acceptor ions by filling in the holes.

- Therefore a net negative charge is established on the P-side of the junction. Thus regions P and N acquire excess negative charge and positive charge respectively.
- The net negative charge established on the P-side of the junction prevents further diffusion of electrons into the P-side. Similarly the net positive charge on the N-side repels the holes crossing the junction from P-side to N-side.
- These impurity ions so produced are fixed in their positions in the crystal lattice in the P and N regions.
- Hence as shown in Fig. 2.22, they form parallel rows or plates of opposite charges facing each other.
- Thus a potential difference is created across the junction. Hence the junction acts as a barrier which restricts further movement of charge carriers. This is called a potential barrier or junction barrier V_B.

Potential barrier (V_B) :

- A potential difference built up across the PN junction which restricts further movement of charge carriers across the junction is known as potential barrier .
- The barrier potential for germanium PN junction is nearly 0.3 V and 0.7 V for silicon PN junction.
- The electrostatic field across the junction caused by the positively charged N-type region tends to drive the holes away from the junction and negatively charged P-region tends to drive the electrons away from the junction.
- Thus on both sides of the junction a layer is formed which is depleted of free electrons and holes. Hence it is called depletion layer. It contains only immobile, positive and negative ions as shown in Fig. 2.22.

Depletion layer :

- A region around the junction from which the charge carriers (free electrons and holes) are depleted is called depletion layer.

2.12.1 Behaviour of a PN Junction Under Biasing :

- When a PN junction is connected across an electric supply (potential difference) the junction is said to be biased.

- The potential difference across the PN junction can be applied in two ways, namely forward biasing and reverse biasing.

2.12.2 Forward Biasing :

- When the positive terminal of a d.c. source or battery is connected to P-type and negative terminal is connected to N-type semiconductor of a PN junction as shown in Fig. 2.23, the junction is said to be in forward biasing.

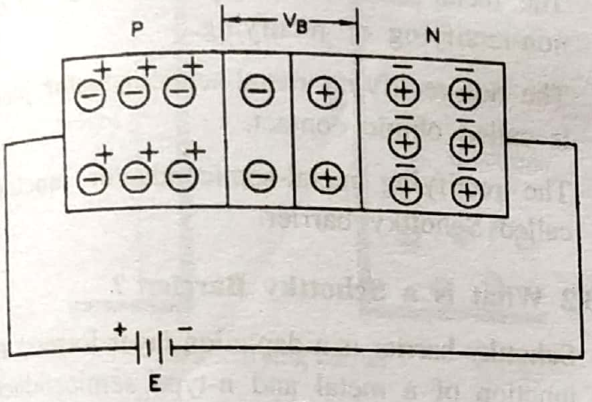


FIG. 2.23 : PN JUNCTION UNDER FORWARD BIAS

- The applied potential with external battery acts in opposition to the internal potential barrier. Under forward bias condition, the applied positive potential repels the holes in P-type region so that the holes move towards the junction and the applied negative potential repels the electrons in the N-type region and the electrons move towards the junction.
- Eventually when the applied potential is more than the internal barrier potential, the depletion region and internal potential barrier disappear. Since the potential barrier voltage is very small (nearly 0.7 V for silicon and 0.3 V for germanium junction) a small forward voltage is sufficient to completely eliminate the barrier.
- Once the potential barrier is eliminated by the forward voltage, current starts flowing easily through the junction. This current is called the forward current.
- The following points are worth noting :

(1) Under forward biasing the potential barrier is reduced and at some forward voltage (0.3 V for Ge and 0.7 V for Si) it is eliminated.

(2) The junction offers low resistance (called forward resistance, R_f) to the flow of current through it.

(3) The magnitude of flow of current through the circuit depends upon the applied forward voltage.

2.12.3 Reverse Biasing :

- When the positive terminal of a d.c. source or battery is connected to N-type and negative terminal is connected to P-type semiconductor of a PN junction as shown in Fig. 2.24 the junction is said to be in reverse biasing.

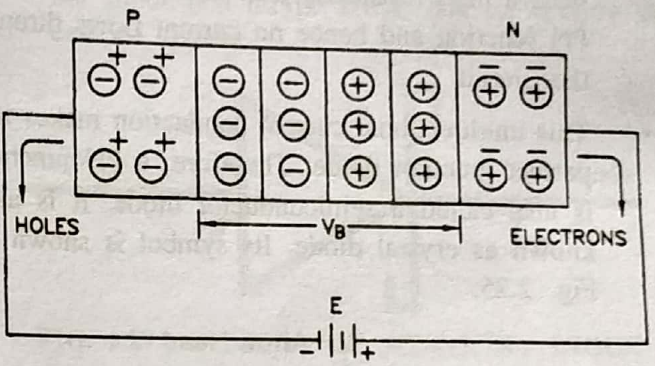


FIG. 2.24 : PN JUNCTION UNDER REVERSE BIAS

- Under applied reverse bias as shown in Fig. 2.24 holes which form the majority carriers of the P-side move towards the negative terminal of the battery and electrons which form the majority carriers of the N-side are attracted towards the positive terminal of the battery.
- Hence the width of the depletion region which is depleted of mobile charge carriers increases.
- Thus the electric field produced by applied reverse bias is in the same direction as the electric field of the potential barrier.
- Hence the resultant potential barrier is increased which prevents the flow of majority carriers in both the directions.
- Therefore, theoretically no current should flow in the external circuit. But in practice, a very small current of the order of a few microamperes flows under reverse bias.
- This current is known as reverse saturation current. The magnitude of reverse saturation current mainly depends upon junction temperature.
- Following points are important to note under reverse biasing :

(1) The junction potential barrier is strengthened.

(2) The junction offers a high resistance (called reverse resistance, R_r) to the flow of current through it.

(3) Practically no current flows in the circuit but a little current (in microamperes) flows through the junction because of minority carriers available even at room temperature.

- From the above discussion, it is concluded that with forward bias, a low resistance path is set up by the PN junction and hence current flows through the circuit on the other hand with reverse bias, a high resistance path is established by the PN junction and hence no current flows through the circuit.
- This unidirectional current conduction makes it a perfect junction diode. Therefore, a PN junction is also called a semiconductor diode. It is also known as crystal diode. Its symbol is shown in Fig. 2.25.

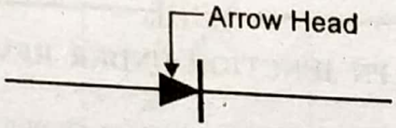


FIG. 2.25 : SYMBOLIC REPRESEN-TATION OF JUNCTION DIODE

Syllabus Topic : Metal-Semiconductor Junction

2.13 METAL–SEMICONDUCTOR JUNCTION :

- In solid-state physics, a metal–semiconductor (M–S) junction is a type of junction in which a metal comes in close contact with a semiconductor material.
- It is the oldest practical semiconductor device.
- M-S junctions can either be rectifying or non-rectifying.
- The rectifying metal–semiconductor junction forms a Schottky barrier, making a device known as a Schottky diode, while the non-rectifying junction is called an ohmic contact.

2.13.1 Metal-semiconductor (M-S) Junction :

- Metal-semiconductor (M-S) junction is a type of junction formed between a metal and an n-type semiconductor when the metal is joined with the n-type semiconductor. Metal-semiconductor junction is also sometimes referred to as M-S junction.

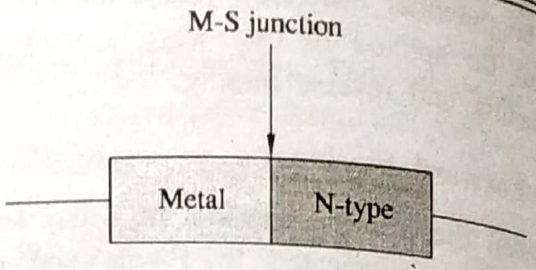


FIG. 2.26 : METAL-SEMICONDUCTOR (M-S) JUNCTION

- The metal-semiconductor junction can be either non-rectifying or rectifying.
- The non-rectifying metal-semiconductor junction is called ohmic contact.
- The rectifying metal-semiconductor junction is called Schottky barrier.

2.13.2 What is a Schottky Barrier ?

- Schottky barrier is a depletion layer formed at the junction of a metal and n-type semiconductor.
- In simple words, schottky barrier is the potential energy barrier formed at the metal-semiconductor junction. The electrons have to overcome this potential energy barrier to flow across the diode.
- The rectifying metal-semiconductor junction forms a rectifying schottky barrier. This rectifying schottky barrier is used for making a device known as schottky diode.
- The non-rectifying metal-semiconductor junction forms a non-rectifying schottky barrier.

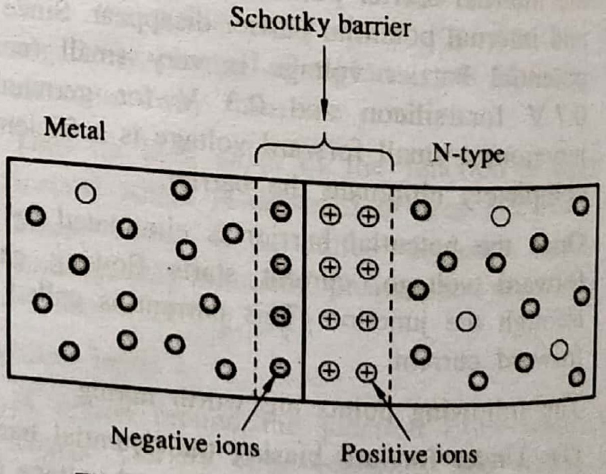
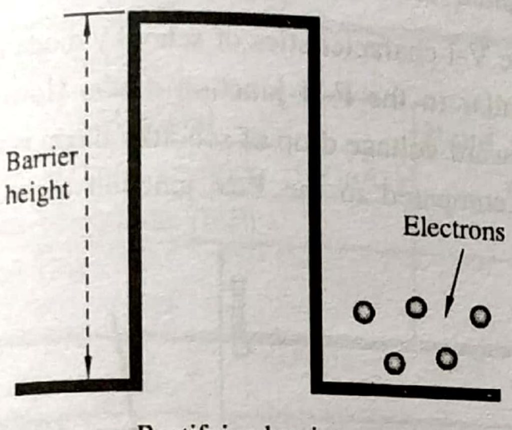


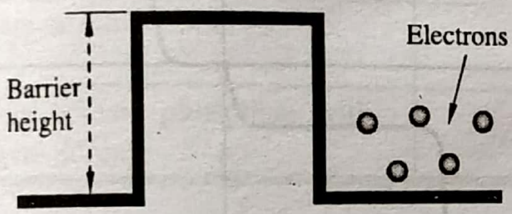
FIG. 2.27 : SCHOTTKY BARRIER

- One of the most important characteristics of a schottky barrier is the schottky barrier height. The value of this barrier height depends on the combination of semiconductor and metal.

- The schottky barrier height of ohmic contact (non-rectifying barrier) is very low whereas the schottky barrier height of non-ohmic contact (rectifying barrier) is high.
- In non-rectifying schottky barrier, the barrier height is not high enough to form a depletion region. So depletion region is negligible or absent in the ohmic contact diode.



Rectifying barrier



Non-rectifying barrier

FIG. 2.28 : RECTIFYING AND NON-RECTIFYING BARRIER

- On the other hand, in rectifying schottky barrier, the barrier height is high enough to form a depletion region. So the depletion region is present in the non-ohmic contact diode.
- The non-rectifying metal-semiconductor junction (ohmic contact) offers very low resistance to the electric current whereas the rectifying metal-semiconductor junction offers high resistance to the electric current as compared to the ohmic contact.
- The rectifying schottky barrier is formed when a metal is in contact with the lightly doped semiconductor, whereas the non-rectifying barrier is formed when a metal is in contact with the heavily doped semiconductor.
- The ohmic contact has a linear current-voltage (I-V) curve whereas the non-ohmic contact has a non-linear current-voltage (I-V) curve.

2.13.3 Schottky Diode Definition :

- Schottky diode is a metal-semiconductor junction diode that has less forward voltage drop than the P-N junction diode and can be used in high-speed switching applications.

2.13.4 Symbol of Schottky Diode :

- The symbol of schottky diode is shown in the below figure. In schottky diode, the metal acts as the anode and n-type semiconductor acts as the cathode.

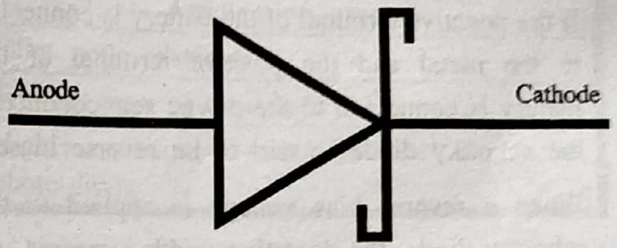


FIG. 2.29 : SYMBOL OF SCHOTTKY DIODE

2.13.5 Forward Biased Schottky Diode :

- If the positive terminal of the battery is connected to the metal and the negative terminal of the battery is connected to the n-type semiconductor, the schottky diode is said to be forward biased.
- When a forward bias voltage is applied to the schottky diode, a large number of free electrons are generated in the n-type semiconductor and metal.
- However, the free electrons in n-type semiconductor and metal cannot cross the junction unless the applied voltage is greater than 0.2 volts.

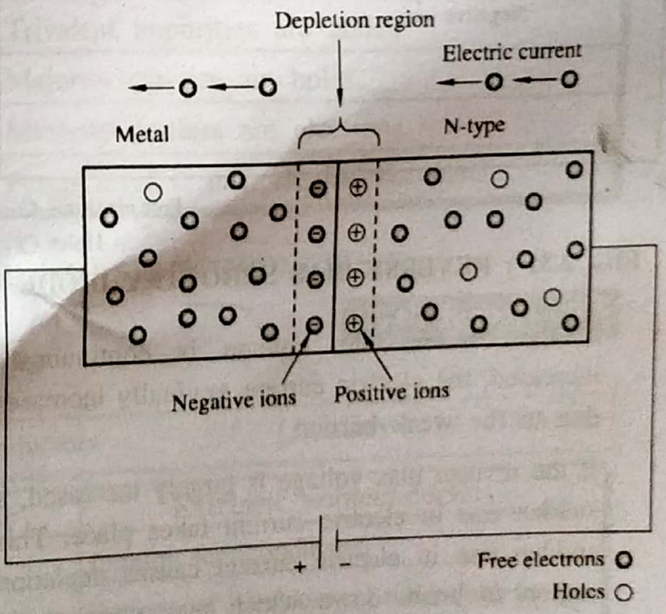


FIG. 2.30 : FORWARD BIASED SCHOTTKY DIODE

- If the applied voltage is greater than 0.2 volts, the free electrons gain enough energy and overcomes the built-in-voltage of the depletion region. As a result, electric current starts flowing through the schottky diode.
- If the applied voltage is continuously increased, the depletion region becomes very thin and finally disappears.

2.13.6 Reverse Bias Schottky Diode :

- If the negative terminal of the battery is connected to the metal and the positive terminal of the battery is connected to the n-type semiconductor, the schottky diode is said to be reverse biased.
- When a reverse bias voltage is applied to the schottky diode, the depletion width increases. As a result, the electric current stops flowing. However, a small leakage current flows due to the thermally excited electrons in the metal.

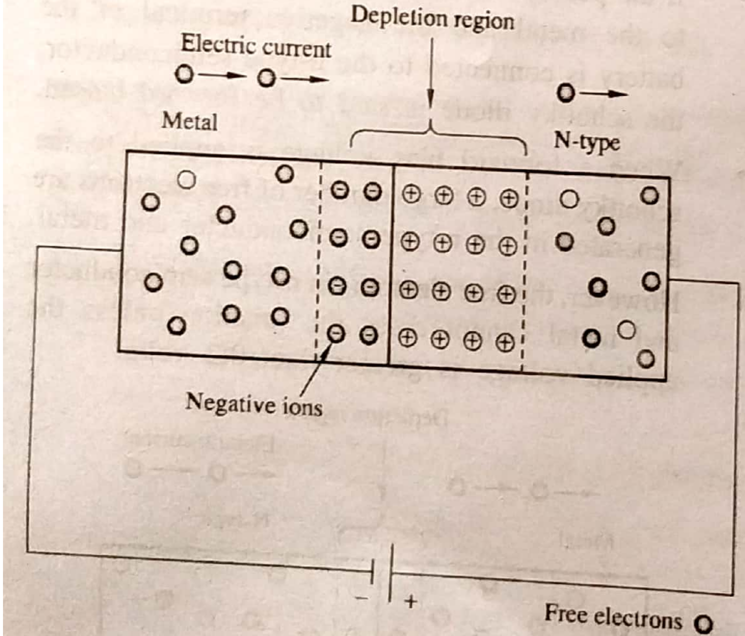


FIG. 2.31 : REVERSE BIAS SCHOTTKY DIODE

- If the reverse bias voltage is continuously increased, the electric current gradually increases due to the weak barrier.
- If the reverse bias voltage is largely increased, a sudden rise in electric current takes place. This sudden rise in electric current causes depletion region to break down which may permanently damage the device.

2.13.7 V-I Characteristics of Schottky Diode :

- The V-I (Voltage-Current) characteristics of schottky diode is shown in the
- below figure. The vertical line in the below figure represents the current flow in the schottky diode and the horizontal line represents the voltage applied across the schottky diode.
- The V-I characteristics of schottky diode is almost similar to the P-N junction diode. However, the forward voltage drop of schottky diode is very low as compared to the P-N junction diode.

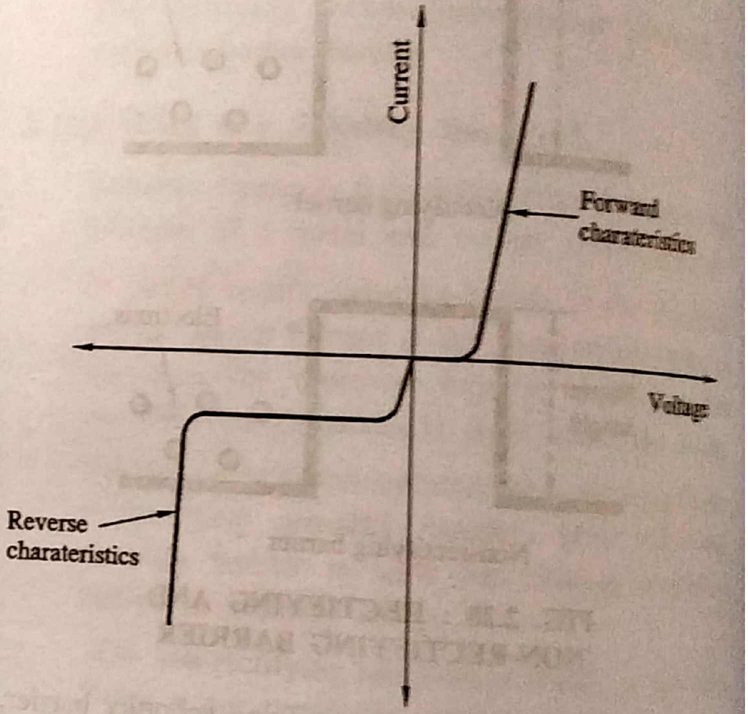


FIG. 2.32 : V-I CHARACTERISTICS OF SCHOTTKY DIODE

- The forward voltage drop of schottky diode is 0.2 to 0.3 volts whereas the forward voltage drop of silicon P-N junction diode is 0.6 to 0.7 volts.
- If the forward bias voltage is greater than 0.2 or 0.3 volts, electric current starts flowing through the schottky diode.
- In schottky diode, the reverse saturation current occurs at a very low voltage as compared to the silicon diode.

Syllabus Topic : Secmiconductor materials of interest for optoelectronic devices

14 SEMICONDUCTOR MATERIALS USED IN OPTOELECTRONIC DEVICES :

1. Photo-conductors :

Material	Band gap (eV)	Application area
Cadmium sulphide (CdS)	2.42	Visible optical range
Germanium (Ge)	0.67	Infrared portion of optical spectrum
Indium antimonide (InSb)	0.18	Infrared portion of optical spectrum

2. Photo-conductors :

Material	Band gap (eV)	Application area
Indium gallium arsenide (InGaAs)	0.75	Fibre optic systems
Indium phosphide (InP)	1.35	Transmission of absorbed light
Silicon (Si)	1.1	Highly sensitive low optical level avalanche photo-diode

3. Light emitting diodes :

Material	Band gap (eV)	Application area
Zinc sulphide (ZnS)	3.6	Ultraviolet optical spectrum
Gallium arsenide (GaAs)	1.43	Infrared emitters in optical communication systems, LASERs (Infrared)
Gallium arsenic phosphide with nitrogen doping	–	Yellow and green LEDs LASERs (visible)

2.15 COMPARISON BETWEEN N-TYPE AND P-TYPE SEMICONDUCTORS : **GTU, January-2019**

GTU Questions

1. Give difference between N type and P type semiconductors. **[January-2019, 3-Marks]**

n-Type	p-Type
1. Pentavalent impurities are added.	1. Trivalent impurities are added
2. Majority carriers are electrons.	2. Majority carriers are holes.
3. Minority carriers are holes.	3. Minority carriers are electrons.
4. Fermi level is near the conduction band.	4. Fermi level is near the valence band.

2.16 DIFFERENCE BETWEEN INTRINSIC AND EXTRINSIC SEMICONDUCTORS :

GTU, January-2019

GTU Questions

1. Give difference between intrinsic and extrinsic semiconductors. **[January-2019, 7-Marks]**

Factors	Intrinsic semiconductor	Extrinsic semiconductor
1. Purity of semiconductor	Pure semiconductor.	Impure semiconductor.
2. Density of electrons	Density of electrons is equal to the density of holes.	Density of electrons is not equal to the density of holes.

3. Electrical conductivity	Electrical conductivity is low	Electrical conductivity is high
4. Temperature effect	Dependence of temperature only.	Dependence on temperature as well as on the amount of impurity only.
5. Impurities	No impurities	Trivalent impurity, pentavalent impurity.
6. Fermi Level	Fermi level lies in between valence and conduction Bands.	Fermi level lies near valence band in p-type and near conduction band in n-type.

EXERCISE

1. Explain with important properties of semiconductors. **(Refer Section-2.1)**
2. Explain concept of Hole in semiconductor ? **(Refer Section-2.2)**
3. Explain Intrinsic Semiconductor in brief. **(Refer Section-2.3)**
4. Explain Carrier concentration in intrinsic semiconductor. **(Refer Section-2.3.4)**
5. Explain Fermi level in intrinsic semiconductor. **(Refer Section-2.4)**
6. How Fermi level varies with respect to temperature in intrinsic semiconductor ? Explain briefly. **(Refer Section-2.4.1)**
7. Explain Extrinsic Semiconductor in brief. **(Refer Section-2.5)**
8. What are the types of Extrinsic Semiconductors based on impurities added ? **(Refer Section-2.5.4)**
9. Explain Fermi level in extrinsic semiconductor. **(Refer Section-2.5.5, 2.5.6 & 2.5.7)**
10. Explain Majority and Minority carriers in n-type semiconductor. **(Refer Section-2.6.6)**
11. Explain Majority and minority carriers in p-type semiconductor. **(Refer Section-2.6.7)**
12. Explain generation and recombination of carriers. **(Refer Section-2.7)**
13. State and explain Law of mass action for semiconductor. **(Refer Section-2.8)**
14. Write short notes on :
    (1) Drift current. **(Refer Section-2.9)**
    (2) Diffusion current. **(Refer Section-2.11)**
    (3) Electron and hole mobility. **(Refer Section-2.10)**
15. Explain P-N junction with forward biasing and reverse biasing circuit. **(Refer Section-2.12)**
16. Explain metal-semiconductor junction in brief. **(Refer Section-2.13)**
17. What are the materials used in optoelectronic devices ? **(Refer Section-2.14)**

GTU QUESTION AND ANSWERS

1. Give difference between N type and P type semiconductors. **(Refer Section-2.15)**
2. Give difference between intrinsic and extrinsic semiconductors. **(Refer Section-2.16)**
3. Explain drift and diffusion current. **(Refer Section-2.9 & 2.11)**
4. Derive expression of electron concentration in conduction band. **(Refer Section-2.3.3 & 2.3.4)**

CHAPTER 3

Light-Semiconductor Interaction

Contents

Syllabus Topic : Absorption

3.1 ABSORPTION OF RADIATION :

GTU, January-2019

GTU Questions

1. Explain emission and absorption. **[January-2019, 4-Marks]**

- Absorption of radiation is the process by which electrons in the ground state absorbs energy from photons to jump into the higher energy level.
- Let us consider two energy levels (E_1 and E_2) of electrons. E_1 is the ground state or lower energy state of electrons and E_2 is the excited state or higher energy state of electrons.
- The electrons in the ground state are called lower energy electrons or ground state electrons whereas the electrons in the excited state are called higher energy electrons or excited electrons.

- In general, the electrons in he lower energy state can't jump into the higher energy state. They need sufficient energy in order jump into the higher energy state.

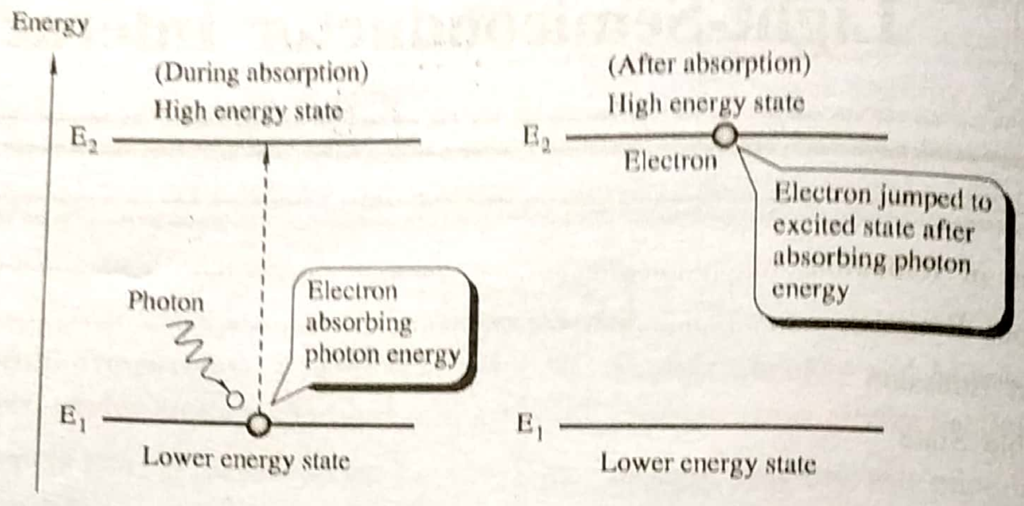


FIG. 3.1 : ABSORPTION OF RADIATION OR LIGHT

- The process is represented as

$$\boxed{\text{Atom} + \text{Photon} \rightarrow \text{Atom}^*}$$

- The frequency of the absorbed photon is

$$\boxed{\nu = \frac{(E_2 - E_1)}{h}}$$

Syllabus Topic : Spontaneous Emission

3.2 SPONTANEOUS EMISSION :

GTU Questions

GTU, January-2019

1. Explain emission and absorption. **[January-2019, 4-Marks]**

- Spontaneous means by "own" or "natural".
- Spontaneous emission is the process by which electrons in the excited state return to the ground state by emitting photons.
- The electrons in the excited state can stay only for a short period (10^{-8} second).

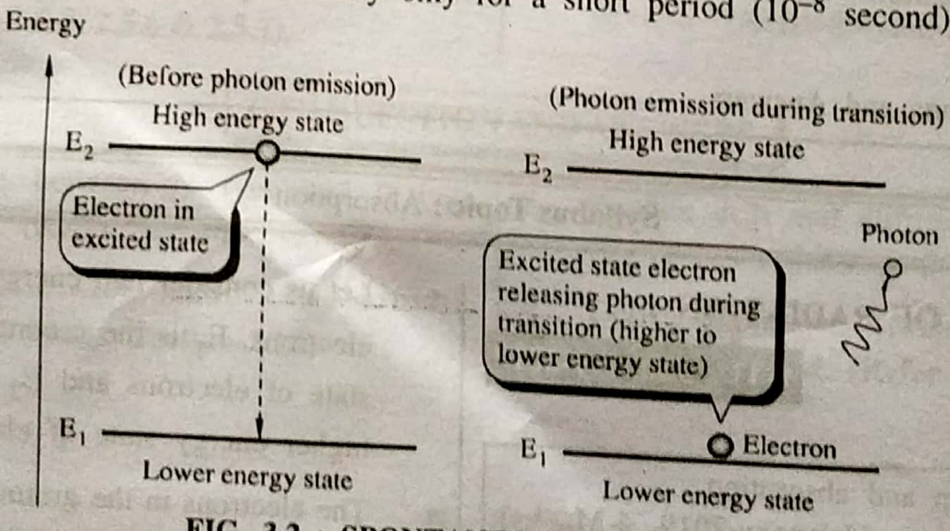


FIG. 3.2 : SPONTANEOUS EMISSION

- Thus, after the short lifetime of the excited electrons, they return to the lower energy state or ground state by releasing energy in the form of photons, this process is known as spontaneous emission.

- The process is represented as

Atom* → Atom + Photon

Syllabus Topic : Stimulated Emission

STIMULATED EMISSION :

- Stimulated means under the influence of some external force.
- Stimulated emission is the process by which incident photon interacts with the excited electron and forces it to return to the ground state.
- In stimulated emission, the light energy is supplied directly to the excited electron instead of supplying light energy to the ground state electrons.
- The stimulated emission is not a natural process it is an artificial process.
- When incident photon interacts with the excited electron, it forces the excited electron to return to the ground state. This excited electron release energy in the form of light while falling to the ground state.

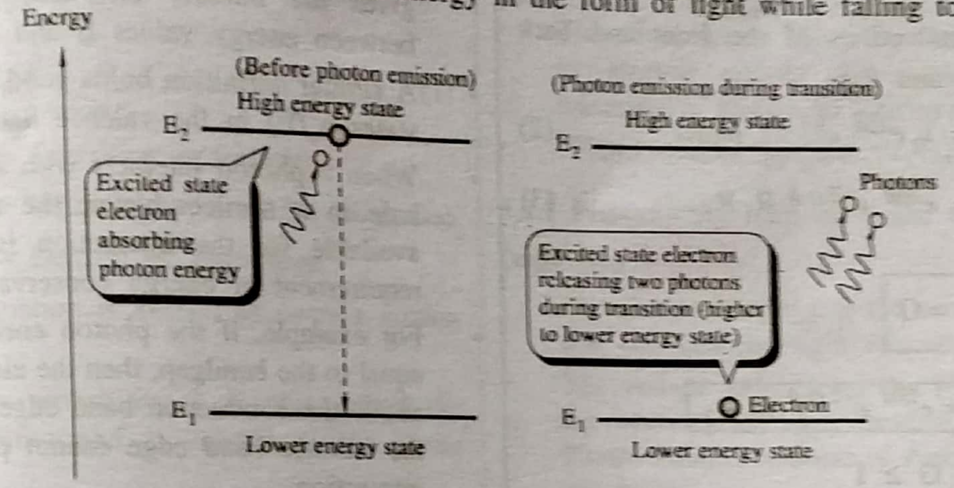


FIG. 3.3 : STIMULATED EMISSION

- The stimulated emission process is very fast compared to the spontaneous emission process.
- The process is represented as

Atom* + Photon → Atom + (Photon + Photon)

3.4 META STABLE STATE :

- It is the state where the atoms get excited and remains in the excited state for longer time than the normal state.

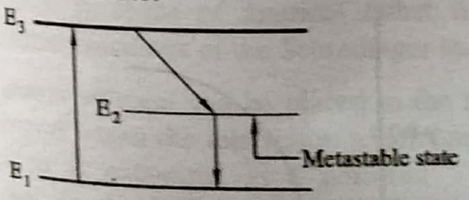


FIG. 3.4 : META STABLE STATE

- This state plays an important role in lasing action.
- In metastable state, atoms stay of the order of 10^{-3} to 10^{-2} second. In excited state other than metastable atom stay of order of 10^{-8} second.
- Let, E_1, E_2, E_3 be the energy levels of the system.
- E_2 is the metastable state of the system.

Syllabus Topic : Gain

3.5 GAIN :

- When atoms come down to ground state from metastable state, they emit photons in random directions.
- When emitted photons incident normally on mirror (optical resonator), they bounce back and forth. So they induce stimulated emission and laser action grows.

- The Laser intensity (I) grows exponentially and intensity on one bounce will be

$$\boxed{I = I_0 e^{2\beta d}} \quad \text{... (1)}$$

where, d = path length in active medium.

β = gain coefficient

I_0 = initial intensity.

- In optical resonator losses are present when light bounces back and forth.
- Light absorption by medium and by mirrors here all loses except reflectance losses may be grouped into a single loss constant α, then intensity loss per unit length when length of medium is *d*.
- Suppose the reflections of the front and back mirrors be R_1 and R_2.

$$\therefore \quad I = I_0 e^{2\beta d} e^{-2\alpha d} R_1 R_2 \quad \text{... (2)}$$

$$\therefore \quad \frac{I}{I_0} = e^{2\beta d} e^{-2\alpha d} R_1 R_2 \quad \text{... (3)}$$

- The gain $\boxed{\frac{I}{I_0} = G}$
- So, $\boxed{G = e^{2\beta d} e^{-2\alpha d} R_1 R_2}$

for laser action $G \geq 1$

$$\boxed{e^{2\beta d} e^{-2\alpha d} R_1 R_2 \geq 1}$$

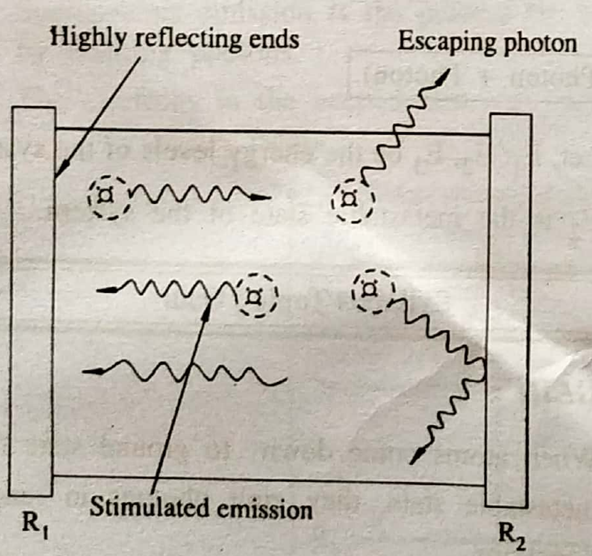


FIG. 3.5 : A LASER CAVITY WITH HIGHLY REFLECTING ENDS SHOWING THE STIMULATED EMISSION OF LIGHT AND THE ESCAPE OF SOME PRIMARY PHOTONS THROUGH THE SIDE WALLS Δν.

Syllabus Topic : Optical joint Density of States / Density of states for photons

3.6 DENSITY OF STATE FOR PHOTONS :

GTU, January-2019

GTU Questions

1. Derive an expression for joint density of states. **[January-2019, 4-Marks]**

- The density of states in a semiconductor refers to the number of allowed electron states per unit volume per unit energy interval.
- Thus, for example, if $\rho_c(E)$ represents the density of states in the conduction band, then $\rho_c(E)\,dE$ gives the number of states per unit volume between energy values E and E + *d*E.
- A similar definition holds good for the density of states $\rho_v(E)$ in the valence band.
- When a photon interacts with an electron and a hole in a semiconductor, the number of states available for the interaction is limited by the requirement of energy conservation.
- For example, if the photon energy is just about equal to the bandgap, then the electron states well above the conduction band edge and well below the valence band edge cannot participate in the interaction.
- The optical joint density of states takes into account the number of states available in both the conduction and the valence bands with which a photon of energy $h\nu$ can interact and is given by

$$\boxed{\rho(\nu) = \frac{(2m_r)^{3/2}}{\pi h^2} (h\nu - E_g)^{1/2} \;;\quad h\nu \geq E_g}$$

where, E_g = band gap

m_r = Reduced mass of the carriers

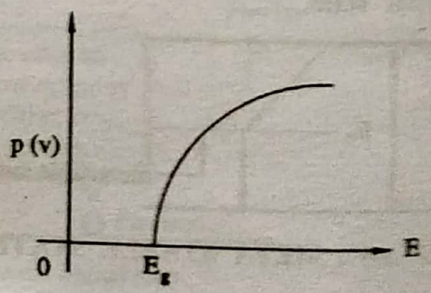


FIG. 3.6 : GRAPH OF P(V) VERSUS E

- Now we will plot a graph (Fig. 3.6) or $\rho(\nu)$ versus E. In this graph when $h\nu > E_g$, it will provide inter band transition.

Syllabus Topic : Transition Rates (Fermi Golden Rule)

3.7 FERMI'S GOLDEN RULE : GTU, Jan. 2019

GTU Questions

1. Discuss fermi golden rule. **[January-2019, 4-Marks]**

- In quantum physics, Fermi's golden rule is used to calculate the transition rate.
- A transition rate depends upon the strength of the coupling between the initial and final state of a system and upon the number of ways the transition can happen (i.e., the density of the final states).
- In many physical situations the transition probability is given by

$$\boxed{\lambda_{if} = \frac{2\pi}{h} |M_{if}|^2 \rho_f} \quad \dots (1)$$

where, λ_{if} = Transition probability

$|M_{if}|$ = Matrix element for the interaction

ρ_f = Density of final state

- The above equation is known as fermi's golden rule.
- The transition probability λ is also called the decay probability and is related to the mean lifetime τ of the state by $\lambda = \frac{1}{\tau}$.
- The general form of Fermi's golden rule can apply to atomic transitions, nuclear decay, scattering ... a large variety of physical transitions.
- A transition will proceed more rapidly if the coupling between the initial and final states is stronger. This coupling term is traditionally called the "matrix element" for the transition : this term comes from an alternative formulation of quantum mechanics in terms of matrices rather than the differential equations of the Schrodinger approach.
- The matrix element can be placed in the form of an integral where the interaction which causes the transition is expressed as a potential V which operates on the initial state wave function.
- The transition probability is proportional to the square of the integral of this interaction over all of the space appropriate to the problem.

$$\boxed{M_{if} = \int \psi_f^* \cdot V \cdot \psi_i \cdot dv} \quad \dots (2)$$

where, V = Operator for the physical interaction which couples the initial and final state of the system.

ψ_f^* = Wave function for final state

ψ_i = Wave function for initial state

- The transition probability is also proportional to the density of final states ρ_f.

Syllabus Topic : Photovoltaic Effect

3.8 PHOTOVOLTAIC EFFECT : GTU, January-2019

GTU Questions

1. What is photovoltaic effect. Explain construction and working of solar cell. **[January-2019, 7-Marks]**

- The effect due to which light energy is converted to electric energy in certain semiconductor materials is known as photovoltaic effect.
- "Photo" means light and "Voltaic" means voltage.

3.8.1 Photovoltaic Cell or Solar Cell :

Definition :

- The photovoltaic cell is the semiconductor device that converts the light into electrical energy.
- The voltage induces by the PV cell depends on the intensity of light incident on it. The name Photovoltaic is because of their voltage producing capability.
- The electrons of the semiconductor material are joined together by the covalent bond. The electromagnetic radiations are made of small energy particles called photons. When the photons are incident on the semiconductor material, then the electrons become energised and starts emitting.
- The energises electron is known as the Photoelectrons. And the phenomenon of emission of electrons is known as the photoelectric effect.
- The working of the Photovoltaic cell depends on the photoelectric effect.

3.8.2 Construction of Photovoltaic Cell :

- The semiconductor materials like arsenide, indium, cadmium, silicon, selenium and gallium are used for making the PV cells. Mostly silicon and selenium are used for making the cell.
- Consider the figure below shows the constructions of the silicon photovoltaic cell.
- The upper surface of the cell is made of the thin layer of the p-type material so that the light can easily. enter into the material.

- The metal rings are placed around p-type and n-type material which acts as their positive and negative output terminals respectively.
- The output voltage and current obtained from the single unit of the cell is very less.
- The magnitude of the output voltage is 0.6 V, and that of the current is 0.8 V. The different combinations of cells are used for increasing the output efficiency.

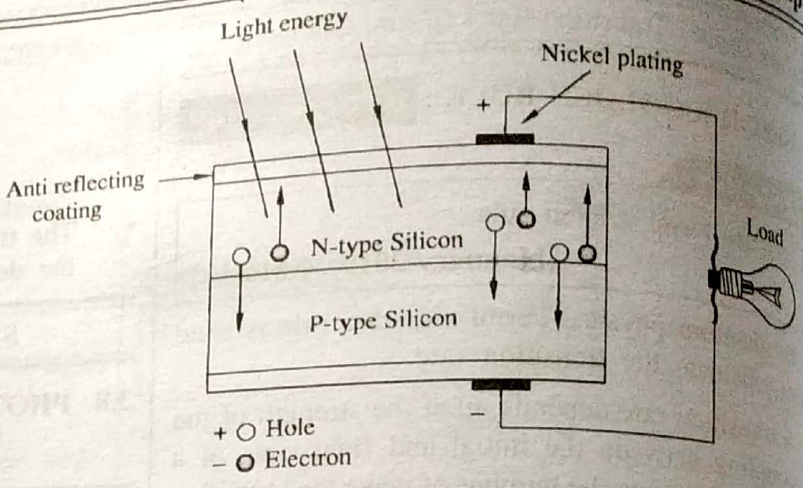


FIG. 3.7 : CONSTRUCTION OF PHOTOVOLATIC CELL

- The solar module is constructed by connecting the single solar cells. And the combination of the solar modules together is known as the solar panel.

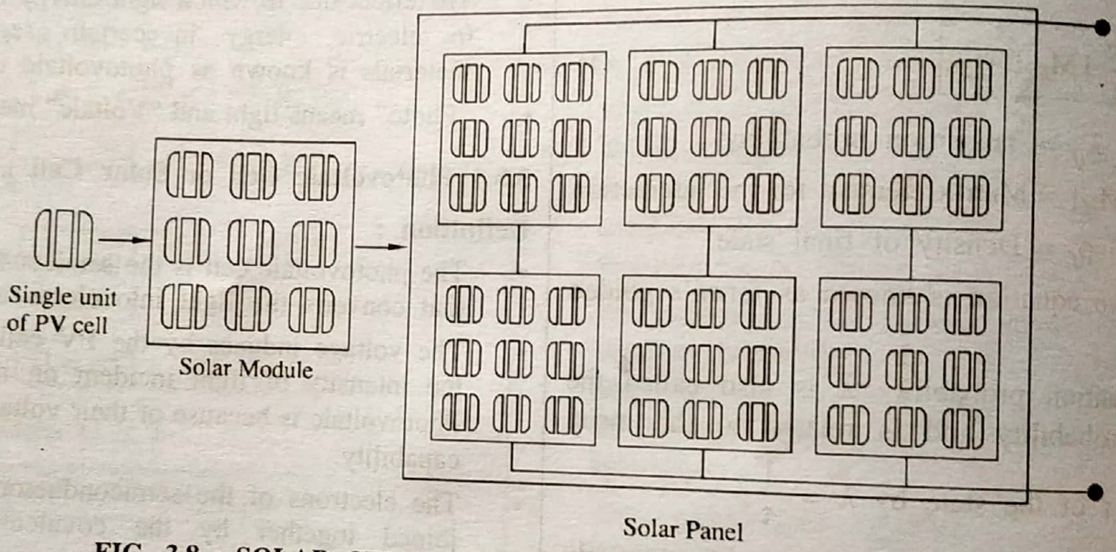


FIG. 3.8 : SOLAR CELL, SOLAR MODULE AND SOLAR PANEL

3.8.3 Working of PV Cell :

- The light incident on the semiconductor material may be pass or reflected through it.
- When the semiconductor material absorbs light, the electrons of the materials starts emitting.
- This happens because the light consists small energise particles called photons.
- When the electrons absorb the photons, they become energise and starts moving into the material.

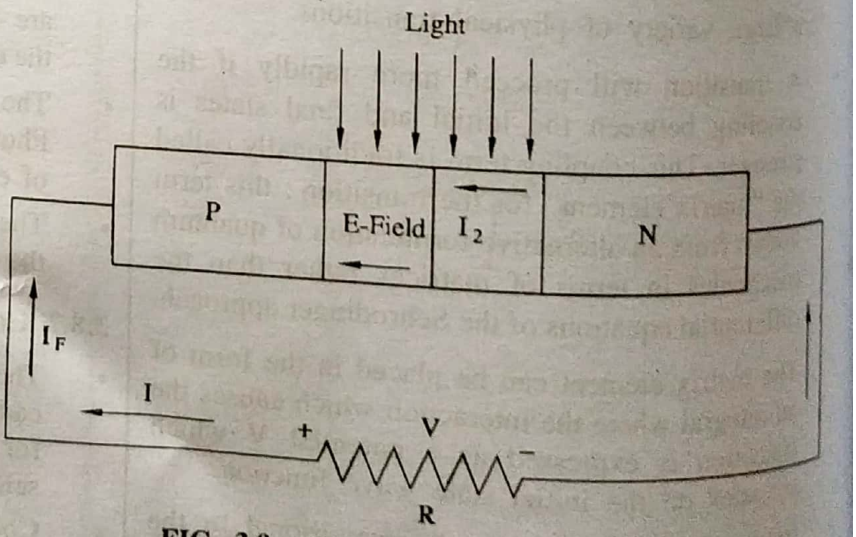


FIG. 3.9 : WORKING OF PV CELL

- Because of the effect of an electric field, the particles move only in the one direction and develops current.
- The semiconductor materials have the metallic electrodes through which the current goes out of it.
- Consider the figure below shows the PV cell made of silicon and the resistive load is connected across it.

- The PV cell consists the P and N-type layer of semiconductor material. These layers are joined together to form the PN junction.
- The junction is the interface the p-type and n-type material. When the light fall on the junction the electrons starts moving from one region to another.

3.8.4 Advantages of Photo Voltaic Technology :

1. Its simple and solid state electronics device which converts directly solar energy into electricity.
2. They do not have any movable mechanical components.
3. The device can be operational without any maintenance for long time.
4. They can be made into modules and arrays suitable to load requirements of any system.
5. No special expertise and skills are required to operate the photo voltaic device.
6. Their reliability of working is quite high.
7. They are the power generators without any pollution of any kind. Hence they give green power.
8. Their applications are very wide ranging from small calculators and mobile devices to space, industries, homes and railways etc.

3.8.5 Disadvantages of Photo Voltaic Technology :

1. Solar cells can generate electricity only during day times. They do not give energy during night times.
2. Electrical energy storage devices like batteries are required when the sun rays are not available during night time or cloudy weather.
3. Efficiency of solar cell varies from 6% to 20% only.
4. The modules and solar panels require large area to install them to any system.

3.8.6 Applications of Solar Photo Voltaic (SPV) Technology :

1. The solar energy is most convenient forms of technology to harness for any small application to very large system like electrical power plants and space technology.
2. Where electrical power grid is not available in remote area, solar photo voltaic panels can supply electrical energy for domestic lighting, water pumps, TV, and mobile towers for communications purposes.
3. Solar Power is frequently used in consumer product applications like calculators and mobiles, which require small amounts of energy.
4. Solar cells are used recreation Vehicles (RVs).
5. Solar cells are also used boating and in battery recharging stations.
6. Large-scale desalination plants can also be PV powered. Larger off-grid systems using an array of PV modules and having more battery storage capacity.
7. Like conventional power plants, central power plants using only solar energy have been installed in the countries like Spain, Italy and U.S., Japan etc.
8. Central power plants using concentrating collectors and heliostats.
9. The unused areas required for installations of SPV modules are rooftops, sunshades, walls balcony and doors and panes used to fix solar panels in office, commercial and domestic buildings.

Syllabus Topic : Optical loss in Photovoltaic Cell

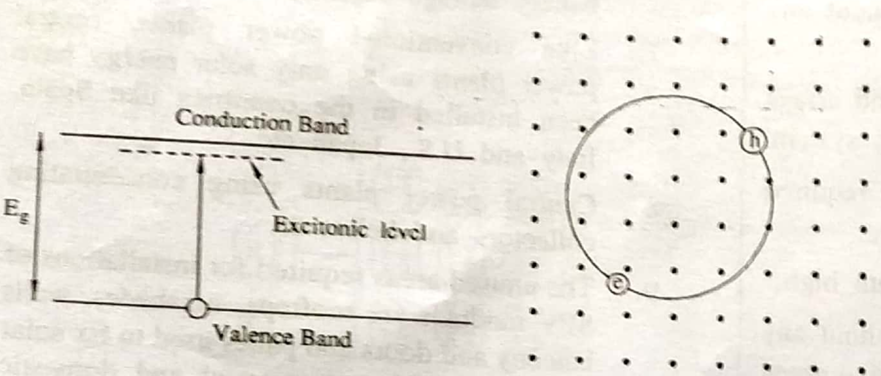
3.9 OPTICAL LOSSES :

- The working efficiency of solar cell is decreased because of following reasons :
  1. Mismatch the bandgap of the material with the solar spectrum.
  2. Reflection loss of light.
  3. Total spectrum of solar energy is not absorbed.
  4. Less intensity of light.
- There are a number of ways to reduce the optical losses :
  1. Top contact coverage of the cell surface can be minimised.
  2. Anti-reflection coatings can be used on the top surface of the cell.
  3. The solar cell can be made thicker to increase absorption.
  4. The optical path length in the solar cell may be increased by a combination of surface texturing and light trapping.

3.10 EXCITON :

- An exciton is a bound state of an electron and an electron hole which are attracted to each other by the electrostatic coulomb force.
- The concept of excitons was first proposed by Yakov Frenkel in 1931, where he described the excitation of atom in a lattice insulators.
- He proposed that this excited state would be able travel in a particle like fashion through the lattice without the net transfer of charge.
- There are two types of exciton.

1. Frenkel exciton
2. Mott-Wannier exciton



(a) Energy level diagram for a typical semiconductor along with the excitation energy level

(b) Mott-Wannier excition in typical lattice

FIG. 3.10

YAKOV FRENKEL

Yakov Frenkel

Yakov Frenkel (1894 – 1952)

He was a Soviet physicist and known for his works in the field of condensed matter physics. He contributed to semiconductor and insulator physics by proposing a theory, which is now commonly known as the Frenkel effect. In 1930 to 1931, Frenkel showed that neutral excitation of a crystal by light is possible, with an electron remaining bound to a hole created at a lattice site identified as a quasiparticle, the exciton.

- When electron hole separation is comparable to lattice constant then exciton is known as Frenkel exciton.
- When electron hole separation is much larger compared to lattice constant, the exciton is known as Mott-Wannier exciton. (Fig. 3.10(b))
- In first case electron-hole pair is tightly bound while in second case electron-hole pair is weakly bound.
- As energy related with the energy gap E_g decides the energy required to create a free electron in conduction band and free hole in valence band then energy gap is slightly greater than the energy of such an exciton. (as shown in Fig. 3.10(a))

3.11 DRUDE MODEL :

GTU Questions

GTU, January-2019

1. Explain Drude model.

[January-2019, 4-Marks]

- The Drude model of electrical conduction was proposed in 1900 by Paul Drude to explain the transport properties of electrons in materials (especially metals).
- The electron theory aims to explain the structure and properties of solids through their electronic structure.
- These valence electrons form an electron gas surround the ion cores and are free to move anywhere within the metals.

3.11.1 Important Point of Drude Model :

1. In an atom, electrons revalue around the nucleus and a metal is, composed of such atoms.
2. The valence electrons of atoms are free to move about the whole volume of the metals like the molecules of a perfect gas in a container. The collection of valence electrons from all the atoms in a given piece of metal forms electrons gas. It is free to move throughout the volume of the metal.
3. These free electrons move in random directions and collide with either positive ions fixed to the lattice or other free electrons. All the collisions are elastic i.e., there is no loss of energy.
4. The movements of free electrons obey the laws of the classical kinetic theory of gases.
5. The electron velocities in a metal obey the classical Maxwell – Boltzmann distribution of velocities.
6. The electrons move in a completely uniform potential field due to ions fixed in the lattice.
7. When an electric field is applied to the metal, the free electrons are accelerated in the direction opposite to the direction of applied electric field.

PAUL DRUDE

Paul Drude

Paul Karl Ludwig Drude (1863 – 1906)

He was a German physicist specializing in optics. He wrote a fundamental textbook integrating optics with Maxwell's theories of electromagnetism. He derived the relationships between the optical and electrical constants and the physical structure of substances. In 1900 he developed a powerful model to explain the thermal, electrical, and optical properties of matter. He explain the transport properties of electrons in materials (especially metals).

3.11.2 Applications of Drude Model :

1. **DC electrical conductivity of metal :**

$$V = IR \; ; \; E = \rho J$$

- Number of electrons with velocity v crossing area A in time dt is $n v A \, dt$; each has charge $-e$; current density is then

$$\boxed{j = -nev} \quad \dots (1)$$

- Electrons are moving randomly; so need to take average velocity for v. In equilibrium average velocity vanishes; no net electrical current. -
- Apply electric field – an electron will have a velocity $v = v_0 - \frac{e \cdot E(t)}{m}$ (t is time since last collision; v_0 is the velocity it came out with after last collision and hence random).
- So,

$$v = v_0 - \frac{e \cdot E(t)}{m}$$

$$= -\frac{eE\tau}{m} \quad \dots (2)$$

- Now, substitue the value of (v) from equation (2) in equation (1), we get

$$j = -nev$$

$$= \frac{ne^2\tau}{m} E$$

$$\boxed{\sigma = \frac{ne^2\tau}{m}} \qquad \left[\because \frac{J}{E} = \sigma\right]$$

- This is the dc conductivity in Drude model.

2. **Hall Effect and Magnetoresistance :**

- Current j_x; magnetic field B_z Lorentz force $-ev \times B$; force same on + Ve and – Ve charges; hence they move on the same side; Hall voltage has different sign for the two types of carriers. Can measure two quantities :

(a) magnetoresistance : $\rho(H) = \frac{E_x}{j_x}$

(b) transverse (Hall) field E_y or Hall coefficient

$$R_H = \frac{E_y}{j_x B_z}$$

3. **Calculate Hall Coefficient and Magnetoresistance :**

- Equations of motion with B_z :

$$\frac{dp}{dt} + \frac{p(t)}{\tau} = -e\left(E + \frac{p \times B}{m}\right).$$

- In steady state current is time-independent and hence :

$$\frac{p(t)}{\tau} = -e\left(E + \frac{p \times B}{m}\right)$$

$$\therefore \quad \frac{p_x}{\tau} = -eE_x - \frac{ep_yB}{m}$$

$$\therefore \quad \frac{p_y}{\tau} = -ey_x - \frac{ep_xB}{m}$$

$$\therefore \quad \sigma_0 E_x = j_x + \omega_c\tau j_y$$

$$\therefore \quad \sigma_0 E_y = -\omega_c\tau j_x + j_y$$

$$\therefore \quad \boxed{E = \frac{1}{\sigma_0}\begin{pmatrix} 1 & \omega_c\tau \\ -\omega_c\tau & 1 \end{pmatrix} j}$$

- For Hall samples; $j_y = 0$;
- So, $R_H = \dfrac{E_y}{j_x B_z} = \boxed{-\dfrac{1}{ne}}$
- In reality, the carrier densities are not always given correctly by the Drude formula; + Ve sign was also not understood till Quantum mechanical theories came in.
- Magnetoresistance is zero according to Drude since $j_x(H) = \sigma_0 E_x = j_x(H)$; not correct in real systems.

4. **AC Electrical Conductivity of Metal :**

- Time dependent electrical field $E_{(t)} = E_0 e^{-i\omega t}$, equation of motion is

$$\frac{dp}{dt} = -\frac{p(t)}{\tau} - eE$$

- Solution $-p(t) = p_0 e^{-i\omega t}$;

$$\therefore \quad -i\omega p_0 = -\frac{p_0}{\tau} - eE_0$$

$$\therefore \quad j = -\frac{nep}{m}$$

$$= \frac{\sigma_0}{1 - i\omega\tau} E$$

$$\therefore \quad \frac{J}{E} = \frac{\sigma_0}{1 - i\omega\tau}$$

$$\therefore \quad \boxed{\sigma(\omega) = \frac{\sigma}{1 - i\omega\tau}}$$

- The AC conductivity $\sigma(\omega) = \dfrac{\sigma_0}{1 - i\omega\tau}$.

EXERCISE

1. Define following terms with respect to Light-semiconductor devices.
   (1) Absorption of radiation. **(Refer Section-3.1)**
   (2) Spontaneous emission. **(Refer Section-3.2)**
   (3) Stimulated Emission. **(Refer Section-3.3)**
   (4) Meta Stable State. **(Refer Section-3.4)**
2. Write short notes on Density of state for photons. **(Refer Section-3.6)**
3. Explain Fermi Golden rule for transition probability. **(Refer Section-3.7)**
4. Explain photovoltaic effect in detail. **(Refer Section-3.8)**
5. Explain the working solar cell with neat diagram. **(Refer Section-3.8.1, 3.8.2 & 3.8.3)**
6. Discuss the advantages and disadvantages of photovoltaic technology and its application. **(Refer Section-3.8.4, 3.8.5 & 3.8.6)**
7. Explain optical losses in photovoltaic cell. **(Refer Section-3.9)**
8. Define and explain exciton. **(Refer Section-3.10)**
9. Write short notes on Drude model. **(Refer Section-3.11)**
10. Explain Drude model and discuss how it is used for D.C. and A.C. conductivity measurement. **(Refer Section-3.11.2(1) & (4))**
11. Explain Drude model and discuss how it is used for Hall measurement and magnetoresistance. **(Refer Section-3.11.2(2) & (3))**

GTU QUESTIONS AND ANSWERS

1. What is photovoltaic effect. Explain construction and working of solar cell. **(Refer Section-3.8)**
2. Derive an expression for joint density of states. **(Refer Section-3.6)**
3. Discuss fermi golden rule. **(Refer Section-3.7)**
4. Explain emission and absorption. **(Refer Section-3.1 & 3.2)**
5. Explain Drude model. **(Refer Section-3.11)**

■ * ■

CHAPTER

4

Measurements

Contents

4.1 FOUR-POINT PROBE METHOD :

GTU, January-2019

GTU Questions

1. Why two probe method for resistivity measurement failed and hence explain four probe method. **[January-2019, 7-Marks]**

- The four-point probe method Fig. 4.1 is used measure the resistivity of semiconducting materials.
- In this method four probes is used.
- The distance between each probes is equal to S.
- A voltmeter is connected between inner two probes.
- A Direct Current source is connected between the outer two probes.
- To measure the resistivity of a sample, a constant current I goes through the outer two probes and the voltage drop between the inner two probes V is measured.
- The differential resistance can be written as :

$$\boxed{dR = \rho\left(\frac{dx}{A}\right)} \qquad \dots (1)$$

where, dR is the resistance between two points with the distance of dx, A is the area that the current goes through and ρ is the resistivity of the sample material.

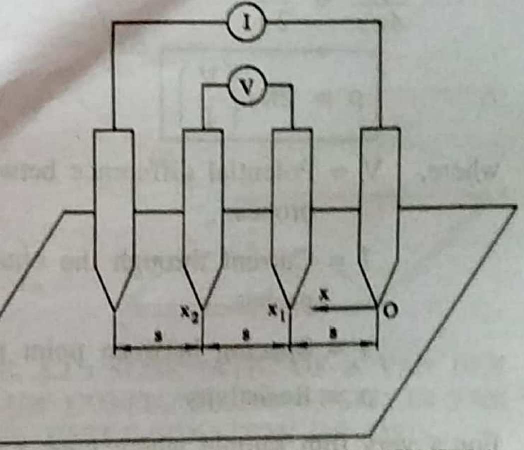


FIG. 4.1 : FOUR-POINT PROBE SYSTEM

- Taking integration on both sides of equation (1), we get

$$R = \int_{x_1}^{x_2} \rho\left(\frac{dx}{A}\right)$$

$$= \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x^2}$$

$$= \frac{\rho}{2\pi}\int_{x_1}^{x_2}\frac{1}{x^2}\cdot dx$$

$$= \frac{\rho}{2\pi}\left(-\frac{1}{x}\right)\Bigg|_{x_1}^{x_2}$$

$$= \frac{\rho}{2\pi}\left[-\frac{1}{x}\right]_{x_1 = s}^{x_2 = 2s}$$

$$= \frac{\rho}{2\pi}\left[-\frac{1}{2s}+\frac{1}{s}\right]$$

$$= \frac{\rho}{2\pi}\left[\frac{-1+2}{2s}\right]$$

$$= \frac{\rho}{2\pi}\left[\frac{1}{2s}\right]$$

$$= \frac{\rho}{4\pi s} \qquad \text{... (2)}$$

where, s equal to the spacing between each probe.

- Due to the superposition of current at the outer two probes, the measured resistance can be calculated by :

$$R = \frac{V}{2\,I} \qquad \text{... (3)}$$

- Compair equation (2) and (3), we get.
- Therefore, the resistivity of a bulk sample is.

$$\frac{\rho}{4\pi s} = \frac{V}{2\,I} \qquad \text{... (4)}$$

$$\therefore \quad \boxed{\rho = 2\pi s\left(\frac{V}{I}\right)}$$

where, V = Potential difference between inner probes.

I = Current through the outer pair of probes.

s = Spacing between point probes.

ρ = Resistivity

- For a very thin sample where $t \ll s$, we get a current ring instead of a current sphere.
- Therefore, the area is the circumference of the circle times the thickness of the sample which gives :

$$A = 2\pi\, x\, t \qquad \text{— (5)}$$

$$R = \int_{x_1}^{x_2} \rho\left(\frac{dx}{A}\right)$$

$$= \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x t}$$

$$= \int_{s}^{2s} \frac{\rho}{2\pi t}\cdot\frac{dx}{x} \quad [\because X_1 = s, X_2 = 2s]$$

$$= \frac{\rho}{2\pi t}\ln(x)\Bigg|_{s}^{2s}$$

$$= \frac{\rho}{2\pi t}[\ln(2s) - \ln(s)]$$

$$= \frac{\rho}{2rt}\left[\frac{\ln(2s)}{s}\right]$$

$$= \frac{\rho}{2\pi t}\ln 2 \qquad \text{— (6)}$$

- Now compair equation (3) with equation (6), we get.
- Again, with the superposition of the current, the resistivity of the thin sample is :

$$\frac{V}{2\,I} = \frac{\rho}{2\pi t}\ln 2$$

$$\therefore \quad \boxed{\rho = \frac{\pi t}{\ln 2}\left(\frac{V}{I}\right)} \qquad \text{— (7)}$$

- The sheet resistance of the sample can be expressed as :

$$\boxed{R_s = \frac{\rho}{t} = \frac{\pi}{\ln 2}\left(\frac{V}{I}\right) = 4.53\left(\frac{V}{I}\right)} \qquad \text{— (8)}$$

where, $\frac{\pi}{\ln 2} = 4.53$

Advantages :

1. To measure very low resistance value, this method is used.
2. In this method, very little contact resistance is associated with the voltage probes so accurate value of the resistivity should be calculated.
3. This method eliminates measurement errors due to the probe resistance.

Applications :

1. Remote sensing areas.
2. Induction hardening process.
3. Accurate goemetry factor estimation.

4.2 VAN DER PAUW METHOD :

- The Van Der Pauw Method is a technique commonly used to measure the resistivity and the Hall coefficient of a sample.
- From the above method, the following properties of the material can be calculated :

1. The resistivity of the material
2. The doping type (i.e. whether it is a P-type or N-type material)
3. The mobility of the majority carrier

- The method was first propounded by Leo J. Van Der Pauw in 1958.
- The following equipments are required :

1. An electromagnet (500 to 5000 Gauss).
2. Constant current source ranging from 10 μA to 100 mA.
3. High input impedance voltmeter ranging from 1 μV to 1 V.
4. Sample temperature measuring probe.

LEO. J. VAN DER PAUW

Leo. J. Van Der Pauw

Leo J. Van Der Pauw was born in Rotterdam. The Netherlands, in December 1927. He received the Ir. degree in physical engineering and the Ph. D. degree in technical sciences from Delft Technical University, Delft, The Netherlands, in 1951 and 1968, respectively.

Since 1953 he has been with Philips Research Laboratories, Eindhoven. The Netherlands, where he has been working in the fields of solid-state physics, computer science, and applied mathematics.

4.2.1 Definitions of Resistivity Measurements :

- Four leads are connected to the four ohmic contacts on the sample.
- They are named as 1, 2, 3 and 4 counter clockwise as shown in Fig. 4.2(a).
- It is important to use the same batch of wire for all four leads in order to minimize the thermoelectric effect.
- Similarly, all four ohmic contacts should consist of the same material.
- We define the following parameters (see Fig. 4.2).

1. ρ = sample resistivity (in Ω · cm)
2. *d* = conducting layer thickness (in cm)
3. I_{12} = positive dc current I injected into contact 1 and taken out of contact 2. Similarly, for I_{23}, I_{34}, I_{41}, I_{21}, I_{14}, I_{43}, I_{32} (in amperes, A)
4. V_{12} = dc voltage measured between contacts 1 and 2 ($V_1 - V_2$) without applied magnetic field (B = 0). Likewise for V_{23}, V_{34}, V_{41}, V_{21}, V_{14}, V_{42}, V_{32} (in volts, V).

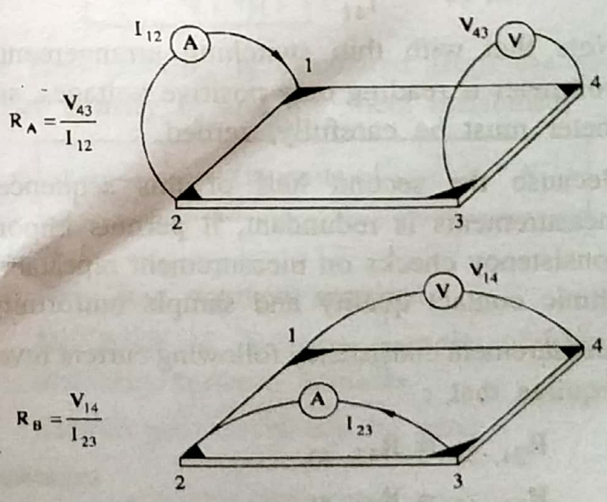


FIG. 4.2 : SCHEMATIC OF A VAN DER PAUW CONFIGURATION USED IN THE DETER-MINATION OF TWO CHARACTERISTICS R_A AND R_B

Syllabus Topic : Resistivity

4.3 RESISTIVITY MEASUREMENTS :

1. Apply the current I_{21} and measure voltage V_{34}.
2. Reverse the polarity of the current (I_{12}) and measure V_{43}.
3. Repeat for the remaining six values (V_{41}, V_{14}, V_{12}, V_{21}, V_{23}, V_{32}).

- Eight measurements of voltage yield the following eight values of resistance, all of which must be positive.

$$R_{21,\,34} = \frac{V_{34}}{I_{21}}$$

$$R_{12,\,43} = \frac{V_{43}}{I_{12}}$$

$$R_{32,\,41} = \frac{V_{41}}{I_{32}}$$

$$R_{23,\,14} = \frac{V_{14}}{I_{23}}$$

$$R_{43,\,12} = \frac{V_{12}}{I_{43}}$$

$$R_{34,\,21} = \frac{V_{21}}{I_{34}}$$

$$R_{14,\,23} = \frac{V_{23}}{I_{14}}$$

$$R_{41,\,32} = \frac{V_{32}}{I_{41}}$$

- Note that with thin switching arrangement the voltmeter is reading only positive voltages, so the meter must be carefully, zeroed.
- Because the second half of this sequence of measurements is redundant, it permits important consistency checks on measurement repeatability, ohmic contact quality and sample uniformity.
- Measurement consistency following current reversal requires that :

$$R_{21,\,34} = R_{12,\,43}$$

$$R_{43,\,12} = R_{34,\,21}$$

$$R_{32,\,41} = R_{23,\,14}$$

$$R_{14,\,23} = R_{41,\,32}$$

- The reciprocity theorem requires that :

$$R_{21,\,34} + R_{12,\,43}$$

$$R_{43,\,12} + R_{34,\,21}$$

and $R_{32,\,41} + R_{23,\,14}$

$$R_{14,\,23} + R_{41,\,32}$$

- If any of the above fail to be true within 5%, investigate the source of error.

4.3.1 Resistivity Calculations :

- The sheet resistance R_s can be determined from the two characteristic resistance

$$R_A = \frac{(R_{21,\,34} + R_{12,\,43} + R_{43,\,12} + R_{34,\,21})}{4}$$

and $$R_B = \frac{(R_{32,\,41} + R_{23,\,14} + R_{14,\,23} + R_{41,\,32})}{4}$$

$$\boxed{R_s = \frac{\pi \cdot R}{\ln 2}} \qquad [\because R = R_A = R_B]$$

- Resistivity, $\rho = R_s \cdot d$

$$= \boxed{\frac{\pi R}{\ln 2} \cdot d}$$

where, R_s = Sheet Resistance
d = Thickness of conducting layer.

4.3.2 Definitions for Hall Measurements :

- The Hall measurement, carried out in the presence of a magnetic field, yields the sheet carrier density n_s and the bulk carrier density n or p (for n-type and p-type sample) if the conducting layer thickness of the sample is known.
- The Hall voltage for thick and heavily doped samples can be quite small (of the order of microvolts).
- The difficulty in obtaining accurate results is not merely the small magnitude of the Hall voltage since good quality digital voltmeters on the market today are quite adequate.
- The more severe problem comes from the large offset voltage caused by non symmetric contact placement, sample shape, and sometimes non uniform temperature.
- The most common way to control this problem is to acquire two sets of Hall measurements, one for positive and one for negative magnetic field direction. The relevant definitions are as follows (Fig. 4.3).

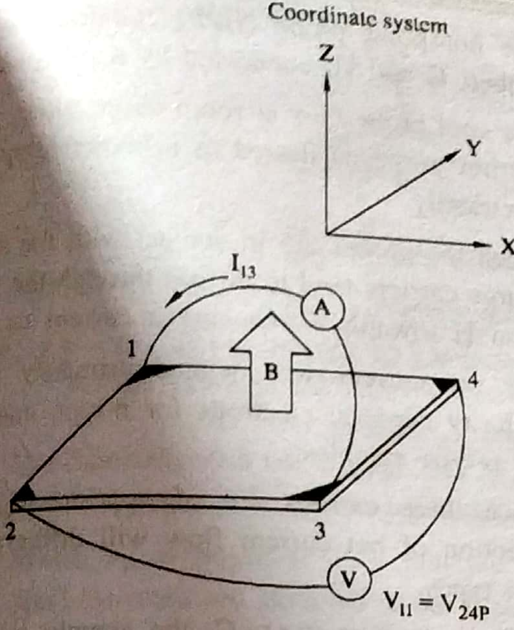


FIG. 4.3 : SCHEMATIC OF A VAN DER PAUW CONFIGURATION USED IN THE DETERMINATION OF THE HALL VOLTAGE VH

I_{13} = dc current injected into lead 1 and taken out of lead 3. Similarly, for I_{31}, I_{32}, I_{24}

B = Constant and uniform magnetic field applied parallel to z-axis (true for positive Z-axis – Ve for – Ve Z-axis).

$V_H = V_{24P}$ = Hall voltage measured between leads 2 and 4 will magnetic field positive for I_{13}, similarly for V_{42p}, V_{13p} and V_{31p}.

- Similar, definitions for V_{24N}, V_{42N}, V_{13N} and V_{31N} apply when the magnetic field B is reversed.

Syllabus Topic : Hall Mobility

4.4 HALL MEASUREMENTS :

- The procedure for the Hall measurement is :
  1. Apply a positive magnetic field B.
  2. Apply a current I_{13} to leads 1 and 3 and measure V_{24P}.
  3. Apply a current I_{31} to leads 3 and 1 and measure V_{42P}.
  4. Similarly, measure V_{13P} and V_{31P} with I_{42} and I_{24} respectively.
  5. Reverse the magnetic field (negative B).
  6. Likewise measure V_{24N}, V_{42N}, V_{13N} and V_{31N} with I_{13}, I_{31}, I_{42} and I_{24} respectively.
- The above eight measurements of Hall voltages V_{24P}, V_{42P}, V_{13P}, V_{31P}, V_{24N}, V_{42N}, V_{13N} and V_{31N} determine the sample type (*n* to *p*) and the carrier density n_s the Hall mobility can be determined from the sheet density n_s and sheet resistance R_s obtained from the resistivity measurement.
- This sequence of measurements is redundant in that for a uniform sample, the average Hall voltage from each of the two diagonal sets of contacts should be the same.

4.4.1 Hall Calculations :

- Steps for the calculations of carrier density and Hall mobility are :
- Calculate the following (be careful to maintain the signs of measured voltages to correct for the offset voltage).

$$V_C = V_{24P} - V_{24N}$$
$$V_D = V_{42P} - V_{42N}$$
$$V_E = V_{13P} - V_{13N}$$
$$V_F = V_{31P} - V_{31N}$$

- The overall Hall voltage is then

$$\boxed{V_H = \frac{V_C + V_D + V_E + V_F}{8}}$$

- The polarity of this Hall voltae indicates the type of material the sample is made of. If it is positive, the mateiral is P-type, and if it is negaitve, the material is N-type.

$$\boxed{n_s = \frac{IB}{q\,|V_H|}}$$

- The Hall mobility is calculated from the sheet carrier density n_s and the sheet resistance,

$$\boxed{\mu = \frac{1}{q n_s \cdot R_s} \text{ (in units of cm}^2\text{ V}^{-1}\text{ S}^{-1}\text{)}}$$

Advantages :

1. Only four contacts required.
2. No need to measure sample widths or distances between contacts.
3. Simple geometries can be used.

Disadvantages :

1. Measurements take about twice as long.
2. Errors due to contact size and placement can be significant when using simple geometries.

4.5 HOT-POINT PROBE MEASUREMENT :

GTU, January-2019

GTU Questions

1. What are hot probe method.
[January-2019, 3-Marks]

- Hot-point probe method is used for determining whether a semiconductor is p-type or n-type.

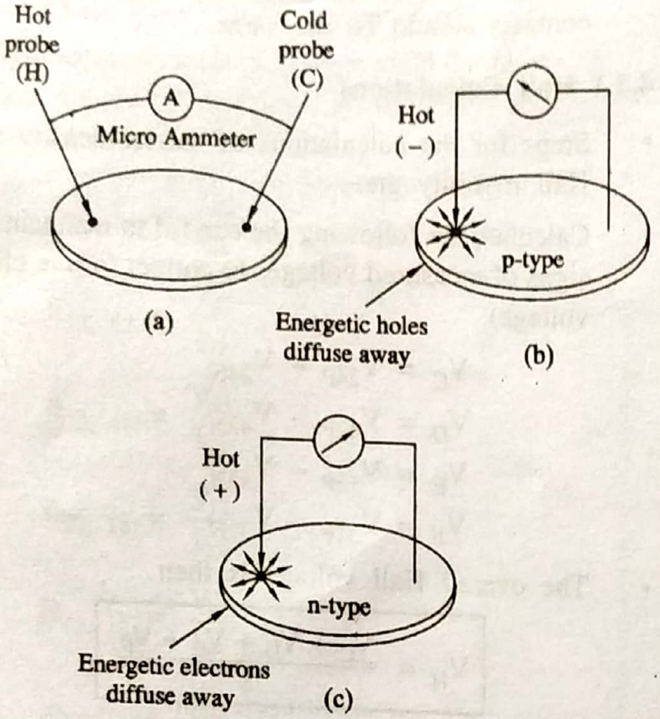


FIG. 4.4 : HOT-POINT PROBE MEASUREMENT

- The hot point probe (HPP) comprises two test probes, C and H, connected by a microammeter.
- The cool probe C is at room temperature, and H, the hot probe, is heated to a higher temperature electrically.
- When the probes are in contact with the sample, charge carriers tend to diffuse through the sample from H towards C, causing a current to flow.
- The net current will depend primarily on the majority carriers, electrons for n-type and holes for p-type samples.
- Since these carriers are of opposite sign, the direction of net current flow will differ for the two types.
- If H is positive w.r.t. C, the sample is n-type (as show in Fig. 4.4(c)), otherwise it is p-type (as show in Fig. 4.4(b)).
- Thus, the type of the sample can be determined by the direction of deflection of a zero-center current meter.

4.6 CAPACITANCE VOLTAGE MEASUREMENT :

- Capacitance voltage measurement (C-V method) is a method for measurement of the barrier capacitance of semiconductor junctions, like p-n junctions, metal-semiconductor junctions and even metal-oxide-semiconductor (MOS) structures.
- In 1942, W. Schottky discovered that impurity distribution can be determined from the C-V measurement.
- This method, is called the C-V technique is widely used to determine impurity distribution of doping profiles of semiconductors devices.
- The C-V technique exploits dependence of width of a space-charge region by a reverse bias.
- This dependence made possible the C-V profiling method on Schottky barrier diodes, P-N junctions, MOS capacitors and MOSFETs.
- Let's consider the asymmetrically doped junction shown in Fig. 4.5.

WALTER HANS SCHOTTKYW

Walter Hans Schottkyw

Walter Hans Schottky (1886 –1976)

Walter Schottky, a famous name in the fields of electronics and physics .He was a German physicist who played a major role in developing the theory of electron and ion emission phenomena. He made many significant contributions in the areas of semiconductor devices, technical physics and technology. He was awarded the Royal Society's in 1936 for his discovery of the Schrot effect.

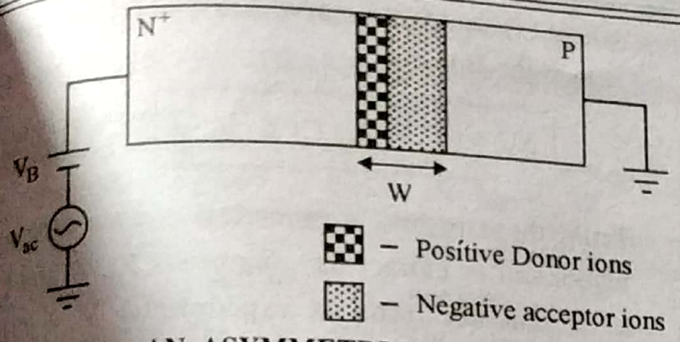


FIG. 4.5 : AN ASYMMETRICALLY DOPED P-N JUNCTION UNDER BIAS CONDITION

- The figure shows a DC voltage bias V_B is applied to the N-side and the P-side connected to ground.
- When V_B is negative (P-N junction is reverse bias) electrons are attracted to the P-side contact, holes are attracted to the other contact.
- As a result, there are more positive donor ions on the N-side, and negative acceptor ions on the P-side appearing at the depletion layer (with reference to the P-N junction in equilibrium).
- For V_B that is more negatively biased, more holes and electrons are attracted to the contacts. This results in an increase in the positive donor and negative acceptor ions at the depletion region.
- This increase in negative bias eventually extends the depletion layer width which in turn increases the depletion-layer charge.
- The reverse bias eventually produces a space-charge region (scr) of width W.
- If the N^+-side is 100 times more heavily doped than the P-side, thus scr spreading into the P-side can be neglected.
- The differential capacitance C is given by

$$\boxed{C = \frac{-dQ_s}{dV}} \quad \text{... (1)}$$

- Negative sign accounts for more negatively charge in the semiconductor scr and Q_s is the semiconductor charge increment. In order for the P-N junction to have overall charge neutrality, dQ_s is given by

$$\boxed{dQ_s = -qAN_A\,(W)\,dW} \quad \text{... (2)}$$

- Combining Equation (1) and (2), we get

$$\boxed{C = \frac{-dQ_s}{dV} = qAN_A(W)\frac{dW}{dV}} \quad \text{... (3)}$$

- In Equation (3), the term $\frac{dN_A(W)}{dV}$ is neglected or is assumed to be zero.
- The capacitance of a P-N junction is given by

$$\boxed{C = \frac{K_s\varepsilon_0 A}{W}} \quad \text{... (4)}$$

where, $K_s\,\varepsilon_0 = 11.7 \times 8.85 \times 10^{-12}$ F/m, A is area of the P-N junction and W is width of the depletion layer.

Advantages of C-V Technique :

1. It is a simple technique where not many equipment are required for extracting the capacitance and voltage.
2. Measurements can be taken directly from the device in which doping profile needs to be evaluated.
3. Doping profile can be extracted with little data processing.
4. It is a non-destruction method as the device is not damaged after measurement.

Disadvantages of C-V Technique :

1. It can only extract doping profile of junction in reverse bias, where conductance is small/negligible.
2. It is an approximation and only works for abrupt junctions.
3. The doping profile near the junction cannot be extracted due to the zero bias space-charge region width.
4. The extracted profile is limited in depth by the voltage breakdown of the device. This is serious in heavily doped regions.
5. It can only extract doping profile of the less highly doped side.
6. Area of device cannot always be accurately determined which affects the doping profile extracted.

4.7 PARAMETER EXTRACTION FROM DIODE I-V CHARACTERISTICS :

- The p-n junction current voltage (I-V) characteristics have been studied for the last twenty years.
- The (I-V) characteristics can be described by the equation :

$$\boxed{I = I_0 \left(e^{(V - R_s I)/A\beta} - 1\right) + \frac{V - R_s I}{R_{sh}}} \quad \text{... (1)}$$

where, $\beta = kT/q$ is the thermal voltage, I_0 is the saturation current, A is the junction ideality factor, R_s and R_{sh} are respectively the series and shunt resistance.

- Equation (1) introduces four parameters I_0, A, R_s, R_{sh} related to internal properties of the electronic device.
- For these junctions, the shunt resistance R_{sh} is very high and the expression $\frac{(V - R_s I)}{R_{sh}}$ is small by comparison with the other terms in equation (1).
- Moreover, the calculations are performed here for voltage values greater than 0.4 V and the term 1 is completely negligible with respect to the exponential term.
- Taking into account these remarks, equation (1) is reduced to :

$$\boxed{V = R_s I + A\beta \ln \frac{I}{I_0}} \quad \text{... (2)}$$

- For this method, a similar equation is considered for another characteristic :

$$\boxed{V' = R'_s I + A\beta \ln \frac{I}{I_0}} \quad \text{... (3)}$$

where the values of the parameters R'_s, A' and I'_0 are arbitrary. Combining equation (2) and (3), the difference $\Delta V = V' - V$ may be written in the form :

$$\boxed{\begin{aligned}\Delta V = (R'_s - R_s)\, I + (A' - A) \cdot \ln I \\ + \beta(A \cdot \ln I_0 - A' \cdot \ln I'_0)\end{aligned}} \quad \text{... (4)}$$

where, $A = A'$, the curve : $\Delta V = f(I)$ becomes a straight line :

$$\boxed{\Delta V = (R'_s - R_s)\, I + \beta \cdot \ln \frac{I_0}{I'_0}} \quad \text{... (5)}$$

- From these results, a numerical process may be elaborated to extract the parameters R_s, A and I_0 of a junction from its experimental $V = f(I)$ characteristics.
- A theoretical characteristic $V' = f(I)$ (equation (3)) is considered with arbitrary values R'_s, A' and I'_0.
- Then, A' is varied to determine the value $A' = A$ so that ΔV becomes a linear function of the current.
- It is performed, while varying A', by seeking the maximum value of the linear correlation coefficient R^2 between the experimental and the theoretical characteristics.
- The slope *a* and the origin ordinate value *b* of the obtained straight line in Eq. (5) yield.

$$\boxed{R_s = R'_s - a} \quad \text{... (6)}$$

and

$$\boxed{I_0 = I'_0 \exp \frac{b}{A\beta}} \quad \text{... (7)}$$

- This procedure leads to obtain, with equation (2) a fairly exact fit to the experimental (I, V) characteristics.
- Fig. 4.6 illustrates this result and shows junction (I, V) characteristics (dotted line)

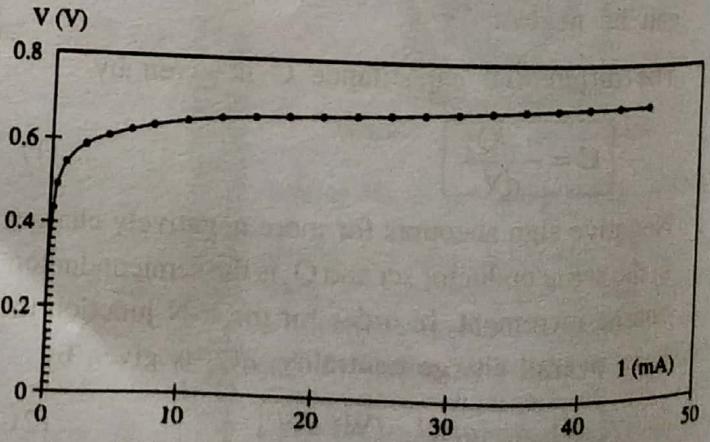


FIG. 4.6 : DESCRIPTION OF THE EXPERIMENTAL (I, V) CHARACTERISTIC (DOTTED LINE) WITH THE ONE EXPONENTIAL MODEL

4.8 DEEP LEVEL TRANSIENT SPECTROSCOPY (DLTS) :

GTU Questions

GTU, January-2019

1. Explain experimental procedure for DLTS.

[January-2019, 7-Marks]

- The Deep Level Transient Spectroscopy (DLTS) is a powerful technology for the detection and identification of electrically active defects (known as traps) in semiconductors.
- These can occur due to contamination or crystal defects.
- DLTS Technique Fig. 4.7 shows how the capacitance transient is generated.
- When a reverse-bias voltage is applied across a Schottky diode, with depletion width W, the charge in the depletion region is contributed by both ionized impurities (shallow states) and deep level (defect) states.
- When a higher bias voltage pulse is applied, the depletion width decreases and there is a corresponding increase in the depletion capacitance.

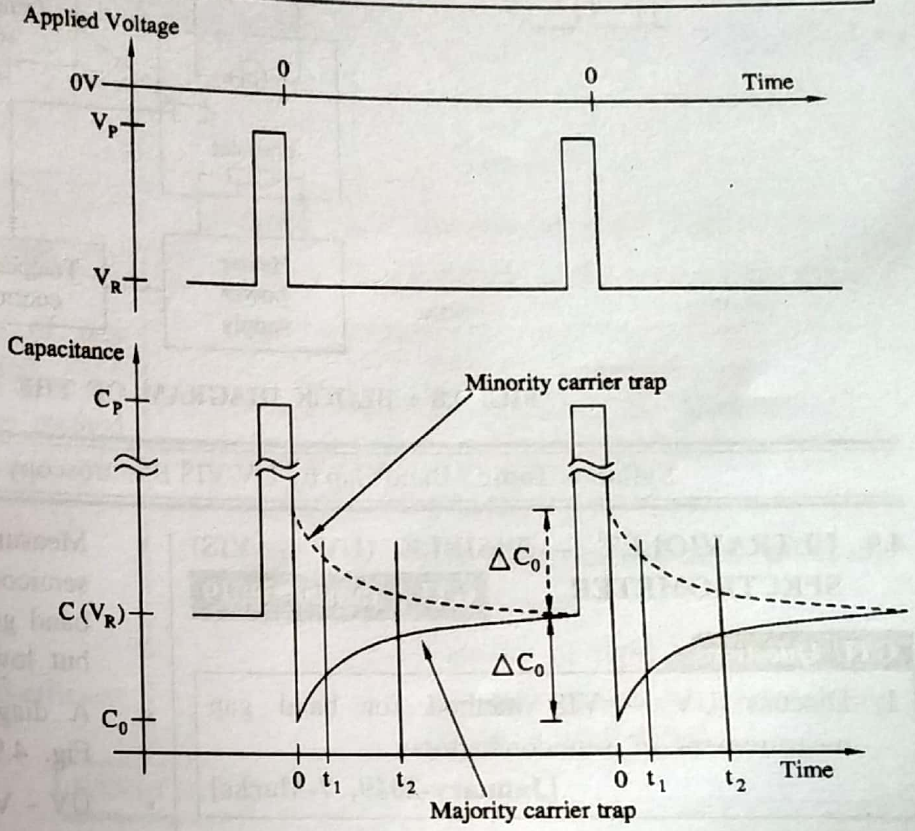


FIG. 4.7 : APPLIED VOLTAGE AND CORRESPONDING CAPACITANCE TRANSIENT

- The deep states below the Fermi level are filled by electron capture during the pulse.
- After the pulse, when the voltage returns to reverse bias, electrons trapped in the deep level states partly counteract the positive charge in the shallow ionized donor states.
- The reverse bias sweeps out the free electrons and therefore increases the width of the depletion region, and the capacitance decreases accordingly.
- As electrons are emitted from trap states, the width of depletion region become slightly smaller and the junction capacitance goes back to the previous steady state value.
- The capacitance transient can be written as

$$\boxed{\Delta C_{(t)} = \Delta C_0 e^{-e_n \cdot t}}$$

where, ΔC_0 = the capacitance difference between $t = 0$

4.8.1 DEEP LEVEL SPECTROMETER :

- A block diagram of the Technologies Deep Level Spectrometer is shown in Fig. 4.8.
- The capacitance meter used a 1 MHz test signal.
- It can tolerate a maximum forward current of 30 mA during the filling pulse, and requires a reverse leakage current of < 100 μA to give an accurate value of the capacitance.

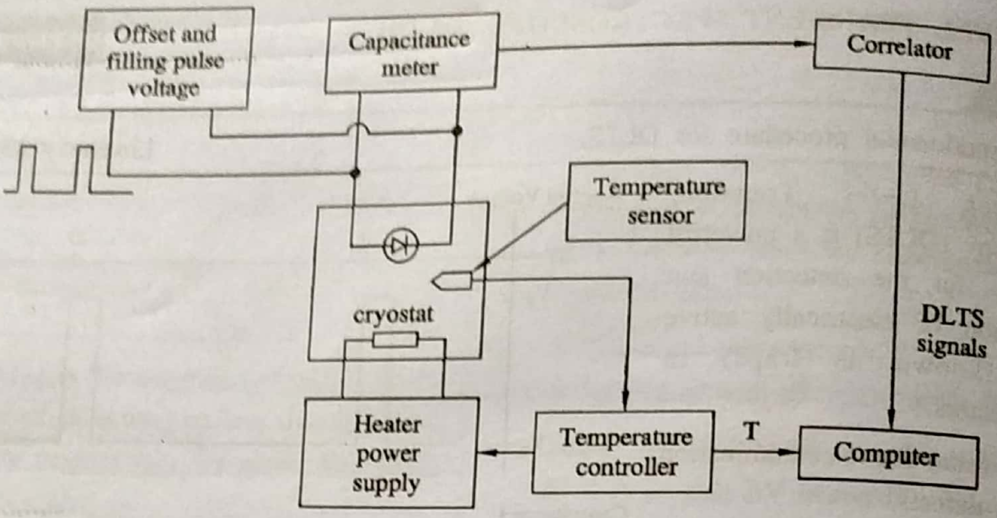


FIG. 4.8 : BLOCK DIAGRAM OF THE DLTS SYSTEM

Syllabus Topic : Band Gap by UV-VIS Spectroscopy Absorption / Transmission

4.9 ULTRAVIOLET – VISIBLE (UV – VIS) SPECTROMETER :

GTU, January-2019

GTU Questions

1. Discuss UV – VIS method for band gap measurement of semiconductors.

[January-2019, 7-Marks]

- To find the energy band gap of different samples by measuring the absorption spectrum, UV – VIS spectrometer is used.
- The term 'band gap' refers to the energy difference between the top of the valence band to the bottom of the conduction band, Fig. 4.9, in which electrons are able to jump from one band to another.

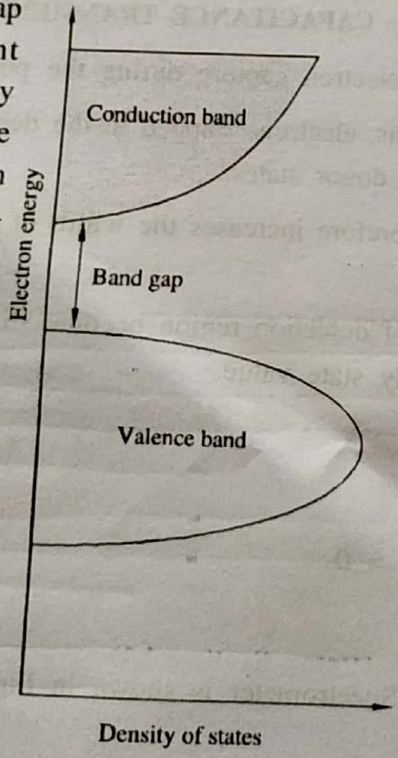


FIG. 4.9 : EXPLANATION OF BAND GAP

- Measuring the band gap is important in semiconductor and nanomaterial industries. The band gap energy for insulators is large (> 4 eV) but lower for semiconductors (< 3 eV).
- A diagram shows the band gap is shown in Fig. 4.9.
- UV - VIS spectrometer measures the intensity of light passing through the sample (I) and compares it to the calibrated intensity (I_0).

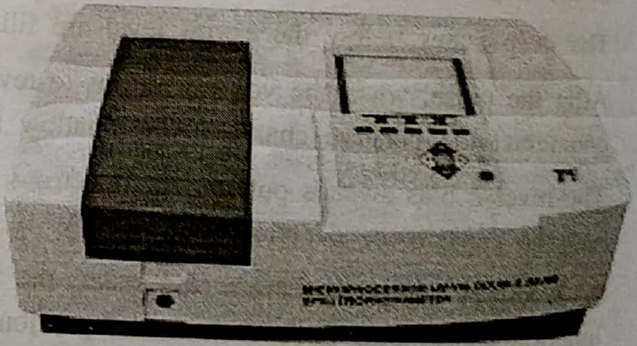


FIG. 4.10 : UV - VIS PHOTO SPECTROMETER

- The ratio $\frac{I}{I_0}$ is called the transmittance for a particular wavelength.
- The absorbance A is defined as,

$$\boxed{A = -\log\left(\frac{I}{I_0}\right)}$$

- The source of UV – VIS light is a tungsten lamp. When the current in the circuit gradually increased from zero.

- The tungsten lamp filament at first can be felt to be emitting warmth, this shows dull red and then gradually brightness until it omits an intense white light.
- Band gap energy,

$$\boxed{E = \frac{hC}{\lambda}}$$

where, $h = 6.62 \times 10^{-34}$ Js

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

- Hence, $E = \frac{1.24 \times 10^{-6}}{\lambda}$ eV, λ in meter
- From the above formula, Band gap of any semiconductor material can be calculated.
- Band gap can be calculated using Trace method as given below :

$$\boxed{\alpha = \frac{A\,(h\nu - E_g)^n}{h\nu}}$$

where, $\alpha = \frac{l_n\left(\frac{1}{T}\right)}{x}$ = absorption co-efficient

T = Transmission

x = thickness of sample

E_g = band gap of the material.

$h\nu$ = Photon Energy

Absorbance :

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

$$I = I_0\, e^{-t/\delta}$$

where, I_0 = Intensity of glass plate

I = Intensity of the coated glass plate/ sample.

t = thickness of sample

δ = Skin depth of the material

$$= \sqrt{\frac{\rho\lambda}{\pi c \mu}}$$

where, ρ = Resistivity (for AC, 2.8×10^{-8} Ω-m)

λ = Wavelength

c = Velocity of light

μ = Absolute magnetic permeability, (1.256×10^{-6} H/m).

EXERCISE

1. Explain the four point probe method for measurement of resistivity of semiconducting materials. **(Refer Section-4.1)**
2. Explain the van der pauw method for measurement of resistivity of the materials. **(Refer Section-4.3)**
3. Explain the how to perform Hall measurement by van der pauw method. **(Refer Section-4.4)**
4. Explain Hot point probe measurement for semiconductor. **(Refer Section-4.5)**
5. Write short notes on C-V measurement and how to determine semiconductor parameter. **(Refer Section-4.6)**
6. Explain diode I-V characteristics. **(Refer Section-4.7)**
7. Write short notes on Deep Level Transient Spectroscopy. **(Refer Section-4.8)**
8. Explain how to measure the band gap of the semiconductor sample using UV-VIS. **(Refer Section-4.9)**

GTU QUESTIONS AND ANSWERS

1. What are hot probe method. **(Refer Section-4.5)**
2. Explain experimental procedure for DLTS. **(Refer Section-4.8)**
3. Why two probe method for resistivity measurement failed and hence explain four probe method. **(Refer Section-4.1)**
4. Discuss UV – VIS method for band gap measurement of semiconductors. **(Refer Section-4.9)**

■ ✻ ■

CHAPTER

5

Superconductivity

Contents

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5.1 INTRODUCTION TO SUPER CONDUCTOR :

GTU, January-2019

GTU Questions

1. Define superconductivity and critical temperature. **[January-2019, 3-Marks]**

- We know the Ohm's law,

$$\boxed{R = \frac{V}{I}}$$

where, R = resistance

V = voltage

I = current

Defination I

- A superconductor is a material that can conduct electricity or transport electrons from one atom to another with no resistance.
- So, in a superconductor, the electric resistance is equal to zero (R = 0).
- So if we putting R = 0 in above equation, we get V = 0.
- So, superconducting materials carry current with no applied voltage.

Superconductor : Defination II

- It is a material that loses all its resistance (offers zero resistance) to the flow of electric current when it is cooled below a certain temperature called the critical temperature (T_c).
- Example : Mercury, Zinc, Niobium, etc.

Critical Temperature (T_c) :

- The temperature at which a material's electrical resistivity drops to absolute zero is called the critical temperature or transition temperature.
- It is denoted by T_c.

Syllabus Topic : Introduction of Superconductivity

5.2 SUPERCONDUCTIVITY :

GTU, January-2019

GTU Questions

1. Define superconductivity and critical temperature. **[January-2019, 3-Marks]**

- Superconductivity was discovered by Dutch Physicist Heike Kamerling Ones in 1911.
- He was awarded the Nobel Prize in Physics in 1913 for his low-temperature research.
- He found that when pure mercury (Hg) was placed in liquid helium, than mercury (Hg) suddenly lost its resistivity at 4.2 K. It was found to be 10^{-5} Ω cm.

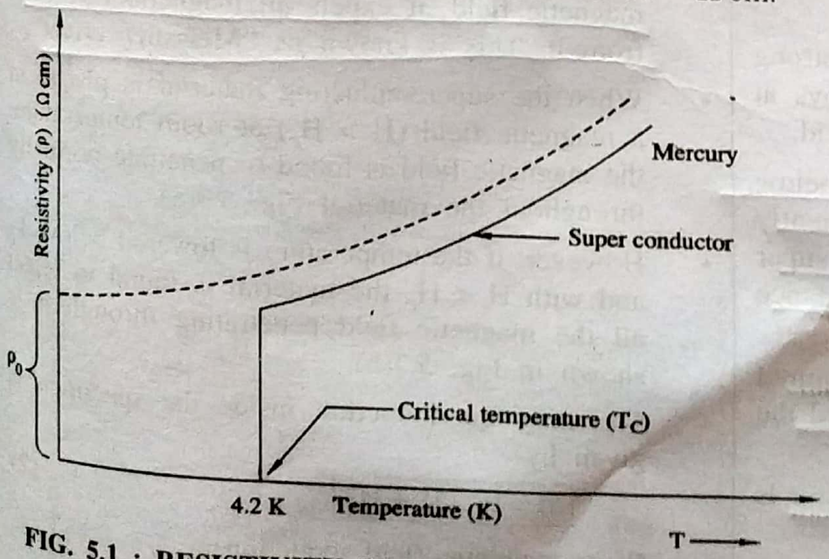


FIG. 5.1 : RESISTIVITY V/S TEMPERATURE FOR SUPERCONDUCTOR AND NORMAL CONDUCTOR

HEIKE KAMERLINGH ONNES

Heike Kamerlingh Onnes

Heike Kamerlingh Onnes (1853 –1926)

He was a Dutch physicist. He discoverered the concept of superconductivity. In 1911 Kamerlingh Onnes measured the electrical conductivity of pure metals (mercury, and later tin and lead) at very low temperatures. He found that at 4.2 K the resistance in a solid mercury wire immersed in liquid helium suddenly vanished. He published articles about the phenomenon, initially referring to it as "supraconductivity" in 1913 he received the Nobel Prize in Physics.

- Some materials lost its resistivity when they are kept below certain temperature. This phenomenon is known as **"Superconductivity"**.

- The value of temperature where resistivity of material becomes zero is known as **"Critical temperature (T_c)"** of that superconducting materials.

Syllabus Topic : Properties of Superconductors

5.3 PROPERTIES OF SUPERCONDUCTORS :

GTU, January-2019

GTU Questions

1. Explain properties of superconductors. **[January-2019, 7-Marks]**

- The various important properties of superconductors are given below :

1. Electrical Resistance
2. Effect of Magnetic Field
3. Meissner Effect
4. Pressure Effect
5. Impurify Effect
6. Isotopic Mass Effect

5.3.1 Electrical Resistance :

- The electrical resistance of a superconducting material is very low and is of the order of $10^{-7}\ \Omega$.

Syllabus Topic : Effect of Magnetic Field

5.3.2 Effect of Magnetic Field :

- When a super conductor is placed in a strong magnetic field, its superconductivity destroys at a particular value of external magnetic field.
- If a substance is in super conducting state below its critical temperature T_c ($T < T_c$) and sufficiently strong magnetic field is applied, the super conductivity state disappears and the substance returns to normal conducting state.
- "The minimum value of magnetic field required to destroy the superconducting state is called the **critical magnetic field H_c**".
- The critical magnetic field of a superconductor is a function of temperature.
- The variation of H_c with temperature is given by

$$\boxed{H_c = H_0\left[1-\left(\frac{T}{T_c}\right)^2\right]} \quad \dots (1)$$

- Where H_0 is the critical field at T = 0 K,
- The critical field decreases with increasing temperature and, becoming zero at $T = T_c$.
- Fig. 5.2 gives the graphs of H_c versus temperature (K).

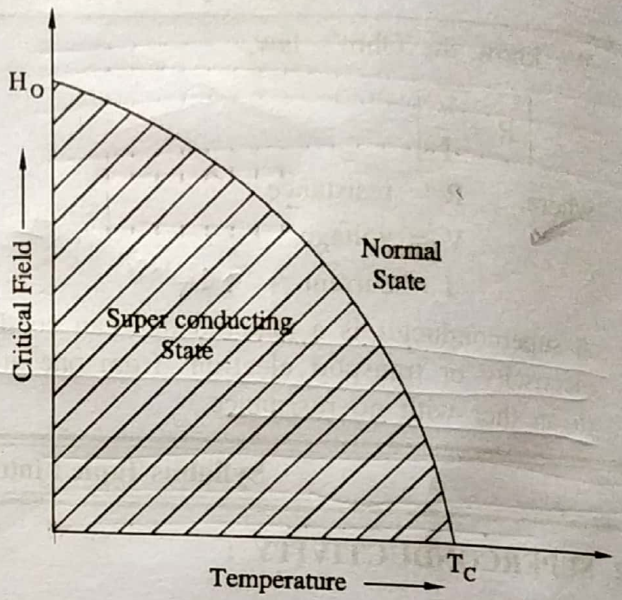


FIG. 5.2

- The material is said to be in the superconducting state within the curve and is non-super-conducting (normal state) in the region outside the curve.

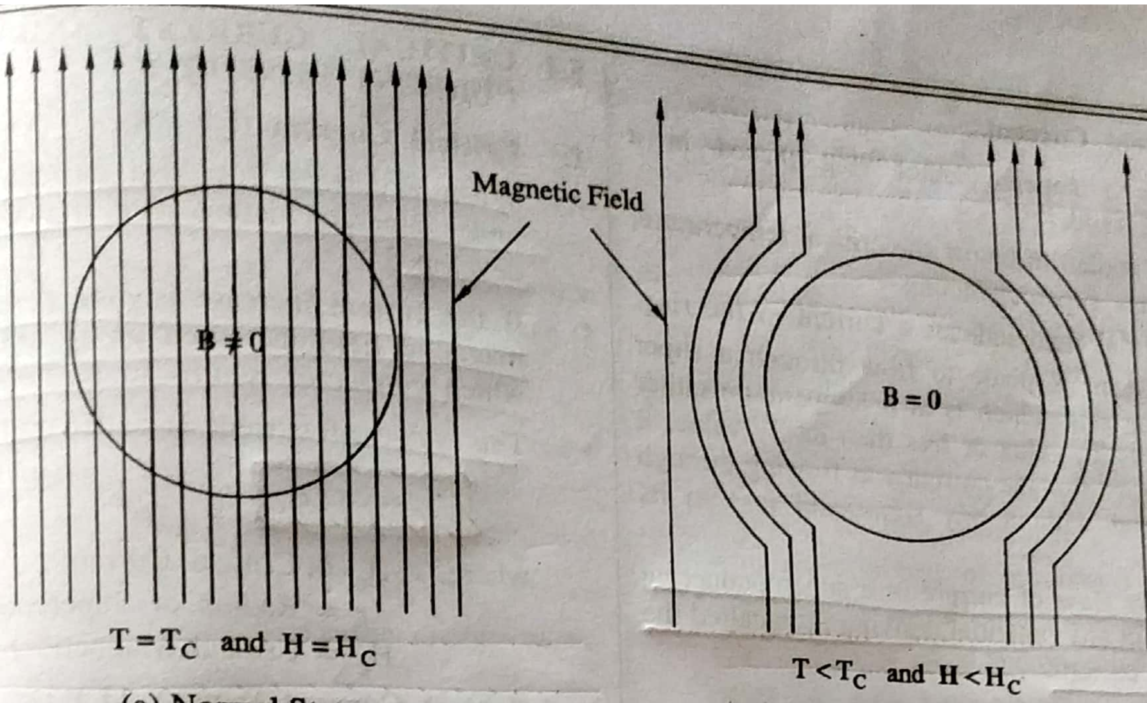
Syllabus Topic : Meissner Effect

5.3.3 Meissner Effect :

- When superconductor is placed in an external magnetic field, it expels all magnetic flux lines from it. This is known as **"Meissner effect"**.
- When the superconducting material is placed in a magnetic field ($H > H_c$) at room temperature, the magnetic field is found to penetrate normally throughout the material Fig. 5.3(a).
- However, if the temperature is lowered below T_c and with $H < H_c$ the material is found to reject all the magnetic field penetrating through it is shown in Fig. 5.3(b).
- The magnetic induction inside the specimen is given by

$$\boxed{B = \mu_0 (M + H)} \quad \dots (2)$$

B = magnetic field induction
H = magnetic field intensity
M = magnetisation vector and
μ_0 = permeability of free space = $4\pi \times 10^{-7}$ H/m



(a) Normal State

(b) Super-conducting State

FIG. 5.3

- We know that B = 0, inside superconductor when $T \leq T_c$.

$$\therefore \quad 0 = \mu_0 (M + H)$$

$$\therefore \quad M = -H$$

$$\therefore \quad \boxed{\frac{M}{H} = -1} \qquad \dots (3)$$

- Magnetic susceptibility (χ_m) is given by,

$$\frac{M}{H} = \chi_m \qquad \dots (4)$$

- So $\chi_m = -1$.
- Thus, this means that, for a super conductor the susceptibility is negative and maximum. i.e. super conductor exhibits perfect diamagnetism.

Syllabus Topic : Impurity Effect

5.3.4 Impurity Effect :

- Impurity of material directly effects critical temperature (T_c) of materiel. As impurity of a material increases, its critical temperature value (T_c) decreases.
- For example, if pure mercury shows superconductivity state at 4.2 K, than impure mercury will show this state below 4.2 K. As impurity increases in mercury, value of T_c will shift towards 0 K.

Syllabus Topic : Pressure Effect

5.3.5 Pressure Effect :

- Some materials behave as superconductors when they are placed under pressure. For example, cesium is not superconductor in normal atmospheric pressure at 1.5 k, but when 110 k bar pressure is applied on Cs, it shows superconductivity, below its T_c value.

Syllabus Topic : Isotopic Mass Effect

5.3.6 Isotopic Mass Effect :

- The critical temperature (T_c) of a superconductor is found to vary with its isotopic mass.
- The relation between T_c and the isotopic mass is given by

$$\boxed{T_c \propto \frac{1}{\sqrt{M}}} \qquad \dots (1)$$

where, M is the isotopic mass.

- i.e. The transition temperature is inversely proportional to the square root of the isotopic mass of a single super conductor.
- The phenomenon of decrease of critical temperature with increasing atomic mass is called isotopic mass effect.

5.3.7 Persistent Current :

- Consider a superconductor ring placed in a magnetic field.
- When it cooled to below the critical temperature, it becomes superconducting.
- The external field induces a current in the ring.
- When current is made to flow through a super conducting ring which is at a temperature either equal to its T_c value or less than its T_c value, it was observed that the current was flowing through the material without any significant loss in its value.
- This steady flow of current in a superconducting ring without any potential deriving it, is called the persistent current.

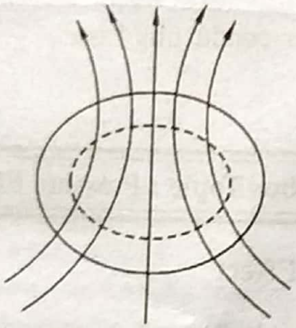


FIG. 5.4 : PERSISTENT CURRENT EFFECT IN SUPERCONDUCTOR

5.4 CRITICAL CURRENT AND CRITICAL CURRENT DENSITY :

1. Critical Current (I_c) :

- When a current is passed through a conductor under superconducting state, a magnetic field is developed.
- If the current increase beyond certain value the magnetic field increased up to critical value at which conductor returns to its normal state.
- This value of current is called critical current.

$$\boxed{I_c = 2\pi r H_c}$$

where, I_c = Critical Current
r = Radius of Superconducting
H_c = Critical Magnetic Field

2. Critical Current Density (J_c) :

- It is defined as the maximum current that can be permitted in a superconducting material without destroying its superconductivity state.
- The relation between critical current density (J_c) and critical current (I_c) is given by

$$\boxed{J_c \propto \frac{I_c}{A}}$$

where, A = Superconductor Cross Section Area

Syllabus Topic : BCS Theory

5.5 BARDEEN, COOPER AND SCHRIEFFER (BCS) THEORY :

GTU Questions

GTU, January-2019

1. Explain mechanism of superconductivity.

[January-2019, 4-Marks]

- This theory was developed by **Bardeen, Cooper** and **Schrieffer**.
- This theory states that the electron experience special kind of attraction Interaction, overcoming the coulomb forces off repulsion between them, as a result Cooper pairs.
- At low temperature, these pairs move without scattering i.e. without any resistance through the lattice points and the materials become superconductor.
- Here the electron – lattice – electron interaction should be stronger than electron – electron interaction.

JOHN BARDEEN • LEON N COOPER • ROBERT SCHRIEFFER

John Bardeen

John Bardeen (1908 –1991)

He was an American physicist and electrical engineer. He is the only person who won the Nobel Prize in Physics twice: first in 1956 with William Shockley and Walter Brattain for the invention of the transistor; and again in 1972 with Leon N Cooper and John Robert Schrieffer for a fundamental theory of conventional superconductivity known as the BCS theory.

Leon N Cooper

Leon N Cooper(1930)

He is an American physicist and Nobel Prize laureate, who with John Bardeen and John Robert Schrieffer, developed the BCS theory of superconductivity.[He is also the namesake of the Cooper pair and co-developer of the BCM theory of synaptic plasticity.

Robert Schrieffer

John Robert Schrieffer (1931)

He was educated at the Massachusetts Institute of Technology, Cambridge.He is an American physicist who, with John Bardeen and Leon N Cooper, was a recipient of the 1972 Nobel Prize in Physics for developing the BCS theory, the first successful quantum theory of superconductivity.

Electron – Lattice – Electron Interaction :

When an electron (1^{st}) moves through the lattice, it will be attracted by the core (+ eV charge) of the lattice. Due to this attraction, ion core is disturbed and it is called as lattice distortion. The lattice vibrations are quantized in terms of phonons.

The deformation product a region of increased positive charge. Thus is another electron (2^{nd}) moves through this region as shown in Fig. 5.5. It will be attracted by the greater concentration of positive charge and hence the energy of the 2^{nd} electron is lowered.

- Hence the two electrons interact through the lattice (or) the phonons field resulting in lowering of energy of the electron. This lowering of energy implies that the force between the two electrons are attractive.
- This type of interaction is called Electrons – Lattice – Electron interaction. The interaction is strong only when the two electrons have equal and opposite momentum and spins.

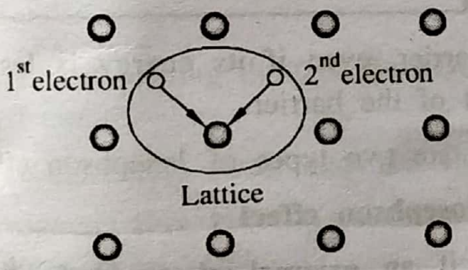


FIG. 5.5

2. **Explanation :**

- Consider the 1^{st} electron with wave vector k distorts the lattice, there by emitting a phonons of wave vector q. This result in the wave vector $k - q$ for the 1^{st} electron.
- Now if the 2^{nd} electron with wave vector k', seeks the lattice, it takes Up the energy from the lattice and its wave vector changes to $k + q$ as shown in Fig. 5.6. Two electrons with wave vector $k - q$ and $k' + q$ from a pair of electrons known as **Cooper pairs**.

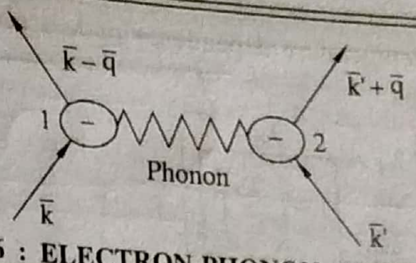


FIG. 5.6 : ELECTRON-PHONON INTERACTION

3. **Cooper pairs :**

- The pairs of electrons formed due to electron – lattice – electron (phonons), electron – electron interaction (forces of attraction) by overcoming the electron – electron interaction (force of repulsion) with equal and opposite momentum and spins i.e., with wave vector $k - q$ and $k' + q$ are called cooper pairs.

4. **Coherence length :**

- In the electron – lattice – electron interactions, the elections will not be fixed, they move in opposite directions and their co-relations may persist over lengths of maximum of 10^{-6} m. This length is called coherence length.

Syllabus Topic : Penetration Depth

5.6 PENETRATION DEPTH :

- When a magnetic field is applied to a super conductor, the applied field does not suddenly drop to zero at the surface.
- Instead the field decays exponentially according to the formula

$$\boxed{H_{(x)} = H_{(0)} e^{\frac{-x}{\lambda}}} \quad \dots (1)$$

where, H_0 = field applied at the surface at $x = 0$.
x = distance from the surface.
λ = the Penetration Depth.

- It is also defined as the distance in which the field decreases by the factor $\left(\frac{1}{e}\right)$.
- The Penetration depth λ varies from 300 to about 5000 Å depending on the material. It is independent of frequency of the magnetic field but it strongly depends on temperature.

- The temperature dependence of λ is given by the relation

$$\boxed{\lambda_T = \frac{\lambda_0}{\left[1-\left(\frac{T}{T_c}\right)^4\right]}} \quad \dots (2)$$

where, λ_T = Penetration depth at T K and λ_0 = Penetration depth at 0 K.

- At low temperatures, λ is nearly independent of temperature. As the temperature approaches the transition temperature λ increases rapidly and approaches infinity.

Syllabus Topic : Josephson Junction

5.7 JOSEPHSON JUNCTION :

- When two superconductor are separated by an insulating layer between them, this is called Josephson Junction (superconductor – insulator – superconductor).

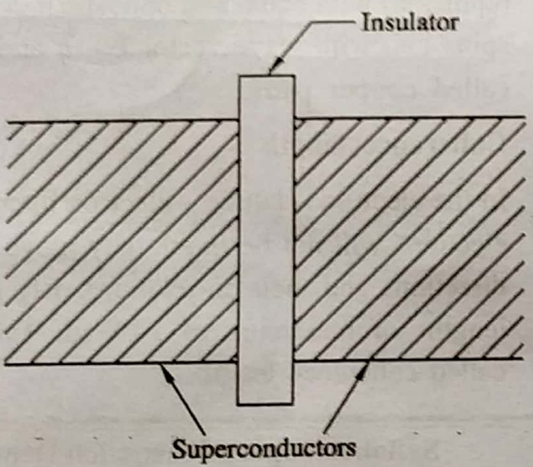


FIG. 5.7

BRAIN DAVID JOSEPHSON

Brain David Josephson

Brian David Josephson (1940)

He is a professor of physics at the University of Cambridge. He is known for his work on superconductivity and quantum tunnelling, he was awarded the Nobel Prize in Physics in 1973 for his prediction of the Josephson effect, made in 1962 when he was a 22-year-old PhD student at Cambridge University.

5.7.1 Josephson Effect :

- When a DC voltage is applied to contact points of superconductors (Fig. 5.8) electrons will flow from one superconductor to another through oxide insulator. This phenomenon is known as "Josephson Effect".

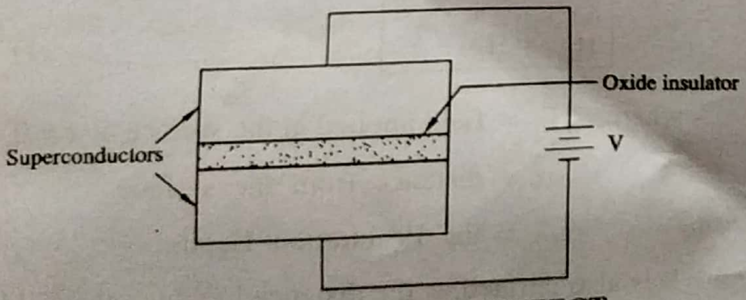


FIG. 5.8 : JOSEPHSON EFFECT

- The insulator normally acts as potential barrier to the flow of electrons from one superconductor to the another superconductor.
- If this barrier is sufficiently thin there is significant probability that an electron can cross the barrier, even if its energy is less than the height of the barrier.
- There are two types of Josephson effect :

1. **DC Josephson effect :**

- Even if an external electrical field has been removed from Josephson junction, DC current flows from one superconductor to another through oxide insulator. This effect is known as "DC Josephson effect".

2. **AC Josephson effect :**

- When an external electric field is applied on both the sides of Josephson junction, current passes from one superconductor to another through oxide insulator with high frequency. This effect is known as "AC Josephson effect".
- If applied potential difference across the junction is 2 eV then frequency of current is given by,

$$\boxed{\nu = \frac{2eV}{h}}$$

5.8 APPLICATION OF JOSEPHSON JUNCTION :

- SQUID works on a principle of Josephson effect.
- SQUID is known as "Superconducting Quantum Interference Device".
- It is a magnetometer which measures small change in magnetic field as well as of voltage.
- When current is passed from one side of superconductor it flows equally through both the branches of SQUID through Josephson junction.

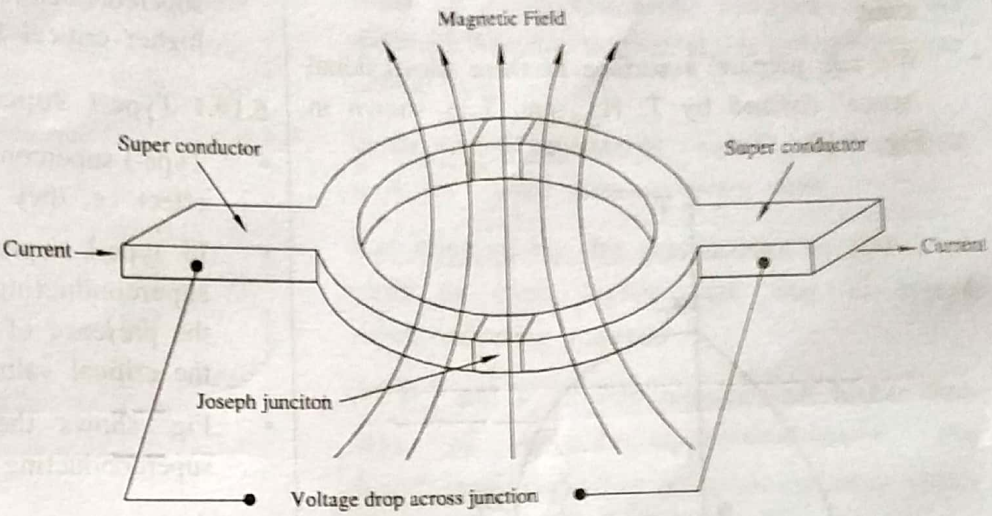


FIG. 5.9 : SCHEMATIC DIAGRAM OF SQUID

- Current passing through the Josephson junctions is very sensitive to magnetic flux. Therefore change in magnetic flux will lead to change in current and hence voltage developed across Josephson junctions.

Construction :

- As shown in Fig. 5.9, two superconductors and thin oxide insulation are arranged in such a way that, they form two parallel Josephson junctions.
- This arrangement is connected to measuring devices which can measure nominal change of voltage and magnetic field across junction.

Working :

- The current passing through the SQUID is very sensitive to magnetic flux passing normally through the closed circuit.
- So, an extremely small magnetic flux can be detected with this device.
- As magnetic flux, current and voltage are dependent on each other, we can measure any one when other is known to us.

Application :

- SQUID can detect very small changes in quantities like voltage (upto order of 10^{-15} V) and magnetic field (upto order of 10^{-21} T).
- It can detect weak magnetic field produced by biological current like human brain.
- It is also used to measure magnetic field of earth and to detect mineral and oil laid inside earth.
- In recent space exploration activity, to detect gravitational waves space shuttle was equipped with SQUID arrangements.

5.9 THREE IMPORTANT FACTORS AFFECTING THE SUPERCONDUCTING STATE :

- The important factors affecting superconducting state are :

1. Critical Temperature T_c
2. Critical Current Density J_c
3. Critical Magnetic field H_c

- Each of these parameters are very dependent on the other two properties. If $T < T_c$, $J < J_c$ and $H_{ext} < H_c$, then there will be superconducting state.
- We can prepare a surface in three dimensional 'space' defined by T, H_{ext} and J as shown in Fig. 5.10.

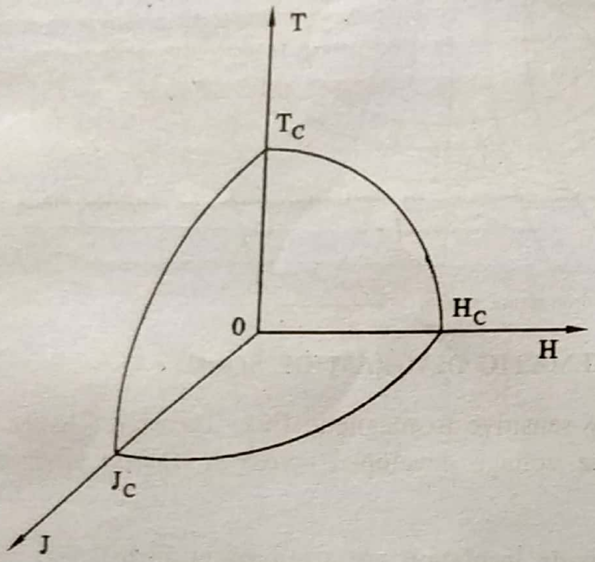


FIG. 5.10

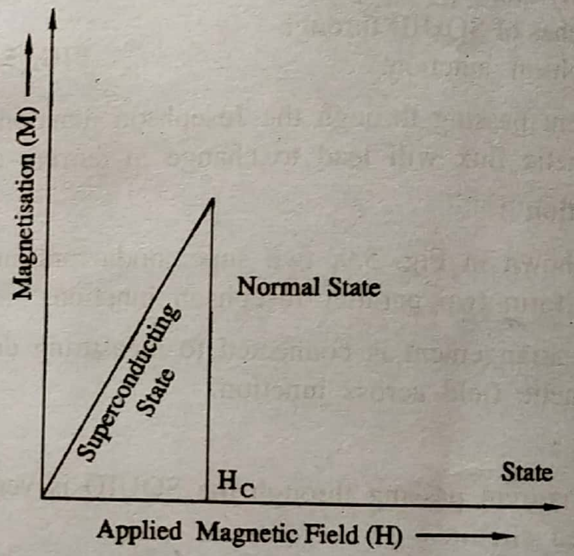
- The highest values for H_c and J_c occur at 0 K, while the highest value for T_c occurs when H and J are zero.
- The surface shown in Fig. 5.10 is called critical surface (T_c, J, H) points within the surface give superconducting state.
- The points outside the surface give normal states.

5.10 TYPES OF SUPERCONDUCTORS :

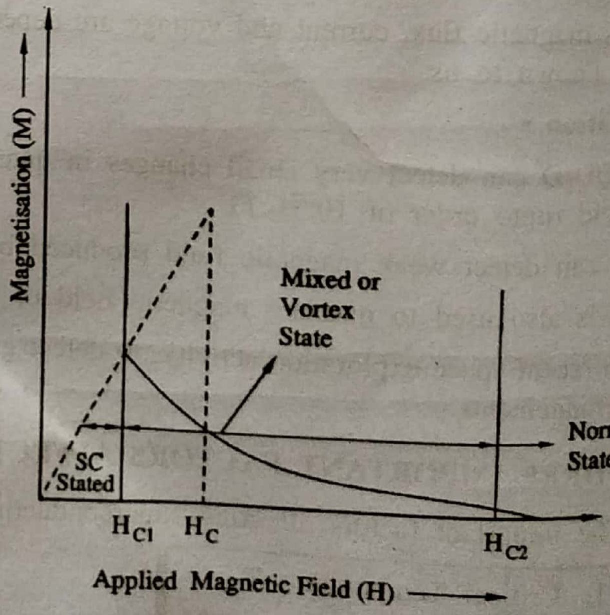
- There are two types of superconductors : Type-I and type-II. There is no difference in the mechanism of superconductivity in both the types. Both have similar thermal properties at the transition temperature in zero magnetic field.
- There are thirty pure metals which exhibit zero resistivity at.
- Low temperatures and have the property of excluding magnetic fields from the interior of the superconductor (Meissner Effect).
- They are called Type-I superconductors. Type-I superconductors are described by the BCS theory.
- Starting in 1930 with lead-bismuth alloys, a number of alloys were found which exhibits superconductivity; they are called type-II superconductors. They were found to have much higher critical fields.

5.10.1 Type-I Superconductors :

- Type-I superconductors exhibit complete Meissner effect i.e. they are completely diamagnetic.
- In type-I superconductors, the transition from superconducting state to normal state in the presence of magnetic field occurs sharply at the critical value of H_c, as shown in Fig. 5.11.
- Fig. shows the magnetization curve for soft superconducting materials.



(a) Type-I superconductor



(b) Type-II superconductor

FIG. 5.11

- The values of H_c for type-I superconducting materials are always too low.
- It shows that the transition at H_c is reversible which means that if the magnetic field is reduced below H_C, the material again acquires the superconducting properly and the magnetic field is expelled.
- Aluminium, lead and indium are examples of Type-I superconductors. The critical field H_c is relatively low for this type.
- Type-I superconductors are also soft superconductors.

Characteristics of Type-I Superconductor :

1. They are perfectly diamagnetic
2. They have only one critical field. At the critical field the magnetization drops to zero.
3. The critical field is of the order of 0.1 Wb/m^2.

Disadvantages :

- Type-I superconductors cannot carry large currents and hence are not of much use in producing high magnetic fields.

5.10.2 Type-II Superconductors :

- Type-II superconductivity was discovered by Schubnikov in 1930s and was explained by Abrikosov in 1957.
- Type-II superconductor, also known as hard superconductor is characterized by two critical fields H_{c_1} and H_{c_2} $[H_{c_1} < H_c < H_{c_2}]$.
- It exists in three states : superconducting, mixed and normal.
- The transition from superconducting state to normal state occurs gradually as the magnetic field is increased from H_{c_1} to H_{c_2}, as shown in Fig. 5.11(b).
- For an applied field below H_{c_1}, the material is perfectly diamagnetic and hence the field is completely excluded. H_{c_1} is called as lower critical field.
- At H_{c_1}, the field starts to thread the specimen and this penetration increase until H_{c_2} is reached at which the magnetization vanishes and the specimen becomes normal. H_{c_2} is called the upper critical field.
- In the region between H_{c_1} and H_{c_2}, the material is in the mixed state or vertex state.
- The value of H_{c_2} for type-II may be 100 times more or even higher than that of type-I superconducting material.
- As H_{c_2} and T_c of this materials are higher than that of type-I superconductors, the type-II superconducting materials are most widely used in all engineering applications.
- This materials are also called as hard superconductors because of relatively large magnetic field requirement to bring them back to their normal state.

Characteristics of Type-II Superconductors :

1. They have two critical magnetic fields. The material is perfect diamagnetic below the lower critical field, H_{c_1}. Meissner effect is complete in this region. Above the upper critical field, H_{c_2}, magnetic flux enters the specimen.
2. They exist in an intermediate state in between the critical fields, H_{c_1} and H_{c_2}. The intermediate state is a mixture of the normal and superconducting state, magnetically bit electrically the material is a superconductor.
3. The upper critical field is very high and is of the order of 200 Wb/m^2.

Applications :

1. They are used in applications of generating very high magnetic fields.

5.10.3 Comparison Between Type-I and Type-II

Type-I Superconductors	Type-II Superconductors
1. These superconductors are called as soft superconductors.	1. These superconductors are called as hard superconductors.
2. They exhibit complete Meissner effect.	2. They do not exhibit complete Meissner effect.
3. Only one critical field exists for these superconductors.	3. Two critical field H_{C1} (lower magnetic field) and H_{c_2} (Upper magnetic field) exists.
4. In type-I, transition at H_c is reversible.	4. In type-II, the state H_{c_1} and H_{c_2}. So above H_{c_2} means between H_{C1} and H_{c_2} transitions is not reversible.
5. The critical field value is very low of the order of 0.1 Tesla.	5. The critical value is very high of the order of 10 Tesla.
6. These materials have limited technical applications because of very lower field strength value.	6. They have wider technological applications because of very higher field strength value.
7. Lead, Tin, Mercury are examples.	7. Nb_3Ge, Nb_3Si etc. are examples.

5.11 HIGH T_c SUPERCONDUCTORS :

- Superconductors are divided into two categories :

1. Low temperature Superconductors
2. High temperature Superconductors

- The term high-temperature superconductor was first discovered by Johnson George Bednorz and Karl Alexander Muller in April 1986, for which they won the nobel prize in Physics.
- They prepared certain compounds of copper oxides and achieve critical temperature upto 30 K. The compound $Y_1Ba_2Cu_3O_7$ (YBCO, 123 compound) was discovered in 1987.
- It had transition temperature 93-95 K. This is above liquid nitrogen (77 K) temperature.
- The superconductors with $T_c > 77$ K are generally known as high temperature superconductors.
- For example $Pb_2YSr_2Cu_3O_8$ [T_c = 77 K] Hg – Ba – Ca – Cu – O compounds [T_c = 130 – 135] etc. the highest transition temperature attained. So far is 138 K in thallium doped mercuric cuprate comprised of Hg, Ti, Ba, Ca, Cu and O.
- The detailed structural investigations of $Y_1Ba_2Cu_3O_6$ crystal is done by X-ray and neutron powder diffraction techniques.
- The structure of this compound is shown in the following Fig. 5.12.

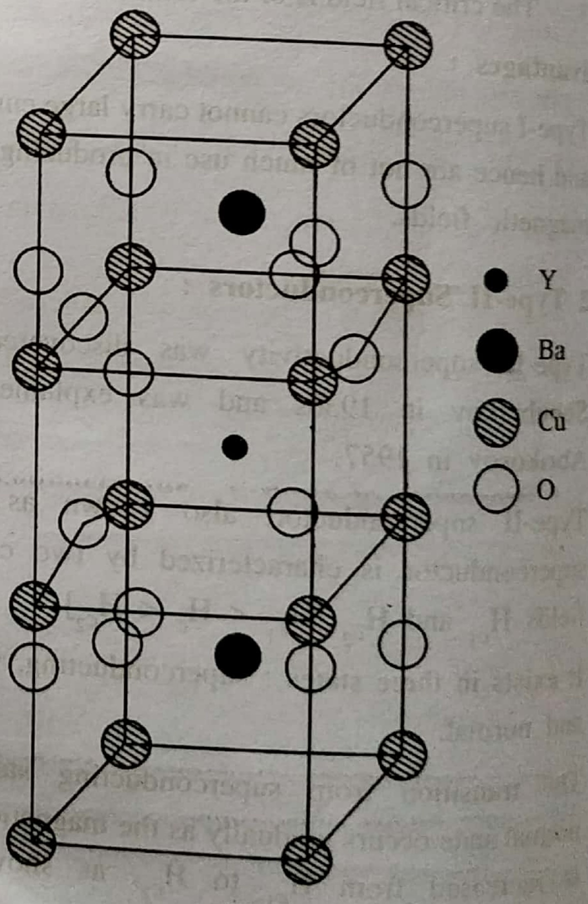


FIG. 5.12

- This figure is the unit cell of crystal of $Y_1Ba_2Cu_3O_6$.
- There is only one Y atom in the unit cell. It is shown by ●.

- There are eight corners of the unit cell. Each corner is common to 8 unit cells.
- Then contribution to each unit cell from each corner $\frac{1}{8}$ atoms. Therefore, contribution to a unit cell from 8 corners is 1 Cu atom denoted by ▨. There are also 8 Cu atoms on the edges. Each edge is common to four unit cells. Hence contribution from each atom on the edge to the cell is $\frac{1}{4}$ atom. Therefore total contribution from edges to the unit cell is 2Cu atoms.

  ∴ Total number of Cu atom is 3. There are two Ba atoms per unit cell and they are denoted by ●.
- There are eight oxygen atoms on vertical edges. Their contribution to unit cell is $\frac{8}{4} = 2$. There are 9 atoms of O on the faces of the unit cell. Each face is common to 2 unit cells. Hence total number of oxygen atoms is $2 + \frac{8}{2} = 6$. Hence, there is one 'molecule' of $Y_1Ba_2Cu_3O_6$.
- Perovskite superconductors which contain CuO planes are highly brittle. They can be grown as ceramic materials. They loose superconductivity by magnetic field which is slightly stronger than the magnetic field of the earth.

5.11.1 Properties of High T_c Superconductors :

- Some of the properties of high T_c Superconductors are as follows :

  1. The high T_c Superconductors are brittle in nature.
  2. The magnetic properties of these materials are highly anisotropic.
  3. The properties of the normal state of these materials are highly anisotropic.
  4. The hall co-efficient is positive indicating that the charge carriers are holes.
  5. The isotope effect is almost absent in these materials.

Syllabus Topic : Applications of Superconductors

5.12 APPLICATIONS OF SUPERCONDUCTORS :

- Due to the unique properties of superconductors they find applications in several fields.

  1. The superconducting wires and cables are used in transmission of electrical power.
  2. It is used to make electrical switching element to switch current between different paths.
  3. Superconducting magnets are capable of generating high fields with low power conduction and they are used for Magnetic Resonance Imaging [MRI] in medical field. Medical Resonance Spectroscopy [MRS] in chemical analysis of body tissues and for various scientific tests and research equipments.
  4. Superconducting generators has the benefit of small size and low energy consumption than the conventional generators.
  5. Type-II superconducting materials are very useful to produce intense magnetic fields. Materials such as Nb-Ti alloys are used to manufacture solenoids. A field of 20 Wb/m^2 can be produces with Nb_3Sn.
  6. They are used to fabricate magnets for high energy particle accelerators, lasers, infrared detectors and other such devices.
  7. **Magnetic Levitation [Maglev] :** Magnetic levitation is the process by which an object is suspended above another object with no other support but magnetic field.
     - The phenomenon of Maglev is based on Meissner effect. We know that in Meissner effect, the magnetic field is pushed out from the superconductor. In simple words, a superconductor repels the magnetic field.
     - By utilization of levitation from magnetic field repulsion they are used in high speed magnetically levitated trains. These trains travel at a speed of about 500 km/h.
  8. Superconductors can act as relay or switching system in a computer. They can also be used as a memory or storage element in computers.

Example-5.1 :

The critical temperature of mercury with isotopic mass 199.5 is 4.185 K. Calculate its critical temperature when its isotopic mass is 203.4.

Solution :

Given $M_1 = 199.5$

$M_2 = 203.4$

$T_{c_1} = 4.185 \text{ K}$

$T_{c_2} = ?$

We know that,

$T_c \propto \frac{1}{\sqrt{M}}$, where M is the isotopic mass.

So, we can write $\sqrt{M_1}\, T_{c_1} = \sqrt{M_2}\, T_{c_2}$

$[\because \sqrt{M_1}\, T_c = \text{constant}]$

$$\Rightarrow \quad T_{c_2} = \left(\frac{\sqrt{M_1}}{\sqrt{M_2}}\right) \times T_{c_1}$$

$$= \sqrt{\frac{199.5}{203.4}} \times 4.185$$

$$\boxed{T_{c_2} = 4.146 \text{ K}}$$

Example-5.2 :

Calculate the critical current flowing through a long thin superconducting wire of radium 0.5 mm. The critical magnetic field is 7.2 KA/m.

Solution :

Given $H_c = 7.2 \text{ KA/m} = 7.2 \times 10^3 \text{ A/m}$

$r = 0.5 \text{ mm} = 0.5 \times 10^{-3} \text{ m}$

$I_c = ?$

We know that

$$I_c = 2\pi r\, H_c$$

$$= 2 \times 3.14 \times 0.5 \times 10^{-3} \times 7.2 \times 10^3$$

$$= \boxed{22.608 \text{ A}}$$

Example-5.3 :

The critical temperature of Sn is 3.7 K. At zero Kelvin the critical field is 0.0306 T. Calculate the critical field at 2 K.

Solution :

Given $T_c = 3.7 \text{ K},$

$H_0 = 0.0306 \text{ T}$

$H_c = ?$

$T = 2 \text{ K}$

We know that

$$H_c = H_0\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

$$= 0.0306\left[-\left(\frac{2}{3.7}\right)^2\right]$$

$$= 0.0306\ [1 - 0.29218]$$

$$= 0.0306 \times 0.70782$$

$$H_c = \boxed{0.021569 \text{ tesla}}$$

Example-5.4 :

The critical field for mercury at $T = 0$ K is 4.1×10^{-2} tesla and 3×10^{-2} tesla at 2.3 K. Calculate the critical temperature.

Solution :

Given $H_0 = 4.1 \times 10^{-2}$ tesla

$H_c = 3 \times 10^{-2}$ tesla

$T = 2.3 \text{ K}$

We know that

$$H_c = H_0\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

$$\therefore \quad \frac{H_c}{H_0} = 1 - \left(\frac{T}{T_c}\right)^2$$

$$\Rightarrow \quad \left(\frac{T}{T_c}\right)^2 = 1 - \frac{H_c}{H_0}$$

$$\Rightarrow \quad T_c^2 = \frac{T^2}{\left[1 - \frac{H_c}{H_0}\right]}$$

$$\Rightarrow \quad T_c = \frac{T^2}{\left[1 - \frac{H_c}{H_0}\right]^{1/2}}$$

$$= \frac{2.3}{\left[1 - \left(\frac{3 \times 10^{-2}}{4.1 \times 10^{-2}}\right)\right]^{1/2}}$$

$$T_c = \boxed{4.44 \text{ K}}$$

Example-5.5 :

A voltage of 2.07 V is applied across a Josephson Junction. Find out the frequency of current across the junction.

Solution :

Given $V = 2.07\ V,\ \nu = ?$

We know that

$$\nu = \frac{2eV}{h}$$

$$= \frac{2 \times 1.6 \times 10^{-19} \times 2.07}{6.62 \times 10^{-34}}$$

$$= \boxed{0.0010 \times 10^{18}\ Hz}$$

Example-5.6 :

Calculate the critical current for a wire of lead having a diameter of 1 mm at 4.2 K. The critical temperature for lead is 7.18 K and $H_{c(0)} = H_0 = 6.5 \times 10^4$ A/m.

Solution :

Given $T = 4.2\ K$

$T_c = 7.18\ K$

$H_0 = 6.5 \times 10^4\ A/m$

$d = 1\ mm = 1 \times 10^{-3}\ m$

We know that

$$H_c = H_0 \left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

$$= 6.5 \times 10^4 \left[1 - \left(\frac{4.2}{7.18}\right)^2\right]$$

$$= 4.28 \times 10^4\ A/m$$

The critical current

$$I_c = 2 \pi r H_c$$

$$= \pi d H_c \qquad [\because \ 2r = d]$$

$$= 3.14 \times 1 \times 10^{-3} \times 4.28 \times 10^4$$

$$I_c = \boxed{134.5\ A}$$

Example-5.7 :

The critical temperature of Nb is 9.15 K. At zero kelvin, the critical field is 0.196 T. Calculate the critical field at 6 K. **GTU, January-2019**

Solution :

Given $T_c = 9.15\ K$

$T = 6\ K$

$H_0 = 0.196\ T$

$H_c = ?$

$$H_c = H_0 \left(1 - \left(\frac{T}{T_c}\right)^2\right)$$

$$= 0.196 \left(1 - \left(\frac{6}{9.15}\right)^2\right)$$

$$= 0.196\ [1 - 0.4299]$$

$$= 0.196\ [0.5701]$$

$$\boxed{H_c = 0.1117\ T}$$

EXERCISE

1. **Define superconductor. (Refer Section-5.1)**
2. **What do you mean by critical temperature in superconductivity ? (Refer Section-5.2)**
3. Explain the properties of superconductors. **(Refer Section-5.3)**
4. Define the followings :
   - (1) Effect of magnetic field. **(Refer Section-5.3.2)**
   - (2) Critical current. **(Refer Section-5.4)**
   - (3) Meissner effect. **(Refer Section-5.3.3)**
   - (4) Mass effect. **(Refer Section-5.3.6)**
   - (5) Critical current density. **(Refer Section-5.4)**
5. What are type-I and type-II superconductors. **(Refer Section-5.9)**
6. Compare type-I and type-II superconductors. **(Refer Section-5.9.3)**

7. What are high T_c superconductors ? Explain the crystal structure of the high T_c superconducting oxide YBCO system. **(Refer Section-5.10)**

8. Explain Josephson effect ? Distinguish between d.c. and a.c. Josephson effects. **(Refer Section-5.6)**

9. Give few important applications of superconductors. **(Refer Section-5.11)**

10. Explain BCS theory. **(Refer Section-5.5)**

GTU QUESTIONS AND ANSWERS

1. Explain mechanism of superconductivity. **(Refer Section-5.5)**

2. Explain properties of superconductors. **(Refer Section-5.3)**

3. Define superconductivity and critical temperature. **(Refer Section-5.1)**

4. The critical temperature of Nb is 9.15 K. At zero kelvin, the critical field is 0.196 T. Calculate the critical field at 6 K. **(Refer Example-5.7)**

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GUJARAT TECHNOLOGICAL UNIVERSITY

QUESTION PAPERS

JANUARY-2019

1. (a) Give assumptions of classical free electron theory. **(Refer Section-1.6)** 03

   (b) Explain mechanism of superconductivity. **(Refer Section-5.5)** 04

   (c) What is photovoltaic effect. Explain construction and working of solar cell. **(Refer Section-3.8)** 07

2. (a) Give difference between N type and P type semiconductors. **(Refer Section-2.15)** 03

   (b) Derive an expression for joint density of states. **(Refer Section-3.6)** 04

   (c) Explain Kronig Penney model in detail. **(Refer Section-1.16)** 07

OR

   (c) Explain properties of superconductors. **(Refer Section-5.3)** 07

3. (a) What are hot probe method. **(Refer Section-4.5)** 03

   (b) Explain fermi levels. **(Refer Section-1.23)** 04

   (c) Explain classification of materials as conductors, insulators and semiconductors. **(Refer Section-1.21)** 07

OR

3. (a) Give difference between intrinsic and extrinsic semiconductors. **(Refer Section-2.16)** 03

   (b) Explain drift and diffusion current. **(Refer Section-2.9 & 2.11)** 04

   (c) Explain direct and indirect band gap with E-k diagrams. **(Refer Section-1.20)** 07

4. (a) Define superconductivity and critical temperature. **(Refer Section-5.1)** 03

   (b) Discuss fermi golden rule. **(Refer Section-3.7)** 04

   (c) Explain diffusion mechanism in detail. 07

OR

4. (a) Define radiative and non-radiative transitions. 03

   (b) Explain emission and absorption. **(Refer Section-3.1 & 3.2)** 04

   (c) Explain experimental procedure for DLTS. **(Refer Section-4.8)** 07

5. (a) The critical temperature of Nb is 9.15 K. At zero kelvin, the critical field is 0.196 T. Calculate the critical field at 6 K. **(Refer Example-5.7)** 03

(b) Explain Drude model. **(Refer Section-3.11)** 04

(c) Why two probe method for resistivity measurement failed and hence explain four probe method. **(Refer Section-4.1)** 07

OR

5. (a) Give success and drawback of classical free electron theory. **(Refer Section-1.11)** 03

(b) Derive expression of electron concentration in conduction band. **(Refer Section-2.3.3 & 2.3.4)** 04

(c) Discuss UV – VIS method for band gap measurement of semiconductors. **(Refer Section-4.9)** 07

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