



MOHAMED SATHAK A.J. COLLEGE OF ENGINEERING

(Approved by AICTE, New Delhi and Affiliated to Anna University, Chennai)



DEPARTMENT OF PHYSICS

(COMMON TO ALL B.E/B.TECH STUDENTS)

PH8252 – PHYSICS FOR INFORMATION SCIENCE



DEPARTMENT OF PHYSICS

MOHAMED SATHAK AJ COLLEGE OF ENGINEERING

CHENNAI – 603103

PH8252 PHYSICS FOR INFORMATION SCIENCE
(Common to CSE & IT)

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OBJECTIVES:

- To understand the essential principles of Physics of semiconductor device and Electron transport properties. Become proficient in magnetic and optical properties of materials and Nano-electronic devices.

UNIT I ELECTRICAL PROPERTIES OF MATERIALS 9

Classical free electron theory - Expression for electrical conductivity – Thermal conductivity, expression - Wiedemann-Franz law – Success and failures - electrons in metals – Particle in a three dimensional box – degenerate states – Fermi- Dirac statistics – Density of energy states – Electron in periodic potential – Energy bands in solids – tight binding approximation - Electron effective mass – concept of hole.

UNIT II SEMICONDUCTOR PHYSICS 9

Intrinsic Semiconductors – Energy band diagram – direct and indirect band gap semiconductors – Carrier concentration in intrinsic semiconductors – extrinsic semiconductors - Carrier concentration in N-type & P-type semiconductors – Variation of carrier concentration with temperature – variation of Fermi level with temperature and impurity concentration – Carrier transport in Semiconductor: random motion, drift, mobility and diffusion – Hall effect and devices – Ohmic contacts – Schottky diode.

UNIT III MAGNETIC PROPERTIES OF MATERIALS 9

Magnetic dipole moment – atomic magnetic moments- magnetic permeability and susceptibility - Magnetic material classification: diamagnetism – Para magnetism – ferromagnetism – antiferromagnetism – ferrimagnetism – Ferromagnetism: origin and exchange interaction- saturation magnetization and Curie temperature – Domain Theory- M versus H behaviour – Hard and soft magnetic materials – examples and uses— Magnetic principle in computer data storage – Magnetic hard disc (GMR sensor).

UNIT IV OPTICAL PROPERTIES OF MATERIALS 9

Classification of optical materials – carrier generation and recombination processes - Absorption emission and scattering of light in metals, insulators and semiconductors (concepts only) - photo current in a P-N diode – solar cell - LED – Organic LED – Laser diodes – Optical data storage techniques.

UNIT V NANO DEVICES 9

Electron density in bulk material – Size dependence of Fermi energy – Quantum confinement – Quantum structures – Density of states in quantum well, quantum wire and quantum dot structure - Band gap of nanomaterials – Tunnelling: single electron phenomena and single electron transistor – Quantum dot laser. Conductivity of metallic nanowires – Ballistic transport – Quantum resistance and conductance – Carbon nanotubes: Properties and applications.

TOTAL :45 PERIODS

OUTCOMES:

At the end of the course, the students will able to

- Gain knowledge on classical and quantum electron theories, and energy band structures,
- Acquire knowledge on basics of semiconductor physics and its applications in various devices,
- Get knowledge on magnetic properties of materials and their applications in data storage,
- Have the necessary understanding on the functioning of optical materials for optoelectronics,
- Understand the basics of quantum structures and their applications in carbon electronics.

TEXT BOOKS:

1. Jasprit Singh, —Semiconductor Devices: Basic PrinciplesII, Wiley 2012.
2. Kasap, S.O. —Principles of Electronic Materials and DevicesII, McGraw-Hill Education, 2007
3. Kittel, C. —Introduction to Solid State PhysicsII. Wiley, 2005.

REFERENCES:

1. Garcia, N. & Damask, A. —Physics for Computer Science StudentsII. Springer-Verlag, 2012.
2. Hanson, G.W. —Fundamentals of NanoelectronicsII. Pearson Education, 2009.
3. Rogers, B., Adams, J. & Pennathur, S. —Nanotechnology: Understanding Small SystemsII. CRC Press, 2014.

UNIT-1 Electrical and Magnetic Properties of materials

Classical free electron theory - Expression for electrical conductivity – Thermal conductivity, expression - Quantum free electron theory :Tunnelling – degenerate states – Fermi- Dirac statistics – Density of energy states – Electron in periodic potential – Energy bands in solids – tight binding approximation - Electron effective mass – concept of hole. Magnetic materials: Dia, para and ferromagnetic effects – paramagnetism in the conduction electrons in metals – exchange interaction and ferromagnetism – quantum interference devices – GMR devices.

ELECTRICAL PROPERTIES OF MATERIALS

Low resistive materials are known as conducting materials. They have high electric and thermal conductivities. The conducting property of a solid is due to the number of valence electrons, which become free electron when they are detached from the parent atom.

Classification of conducting materials:

Based on their conductivity conducting materials are classified into three types.

- Zero resistivity materials
- Low resistivity materials
- High resistivity materials

ELECTRON THEORY OF SOLIDS: The electron theory of metals aims to explain the structure and properties of solids through their electronic structure. The electron theory is applicable to all solids i.e., both metals and non-metals. It explains the electrical, thermal and magnetic properties of solids etc.

The theory has been developed in three main stages.

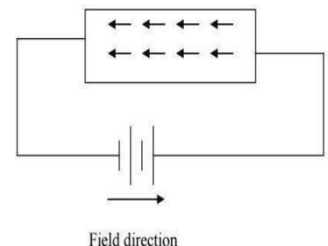
The classical free electron theory: Drude and Lorentz proposed this theory in 1900. According to this theory, the metals containing the free electrons obey the laws of classical mechanics.

The quantum free electron theory: Somerfield developed this theory in 1928. According to this theory the free electrons obey quantum laws. According to this theory the free electrons are moving in a constant potential.

The zone theory: Bloch stated this theory in 1928. According to this theory, the free electrons move in a periodic field provided by the lattice.

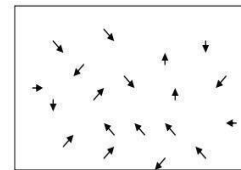
POSTULATES OF CLASSICAL FREE ELECTRON THEORY

In the absence of electrical field: When an electrical field is not applied, the free electrons move everywhere in a random manner. They collide with other free electrons and positive ion core. This collision is known as elastic collision.



UNIT-2 Electrical and Magnetic Properties of materials

In the presence of electric field: When the electrical field is applied, the electrons get some amount of energy from the applied electric field and they begin to move towards the positive potential.



Since electrons are assumed to be a perfect gas, they obey the laws of kinetic theory of gases.

Drift velocity: It is defined as the average velocity acquired by the free electrons in a metal in a particular direction by the application of an electrical field.

$$v_d = \frac{\lambda}{\tau_c}$$

Collision Time: The average time taken by a free electron between any two successive collisions is known as collision time.

$$\tau_c = \lambda / v_d$$

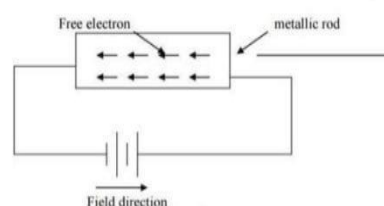
Mean free path: The average distance travelled by a free electron between any two successive collisions in the presence of an applied field is known as mean free path. It is the product of drift velocity of electrons (v_d) and collision time (τ_c). $\lambda = v_d \times \tau_c$

Relaxation time: The average time taken by a free electron to reach its equilibrium position from its disturbed position due to application of an external electric field is called relaxation time. It is approximately equal to 10^{-14} second.

Electrical conductivity of a metal

Definition: It can be defined as the quantity of electric charge (Q) conducted per unit time (t) across unit area (A) of the solid for unit applied electric field (E).

$$\sigma = \frac{Q}{tAE} \Omega^{-1} \text{m}^{-1}$$



Derivation: We know in the absence of external electric field, the motion of electrons in a metal moves randomly in all directions. When an electric field is applied between the two ends of a metallic rod. The electrons will move towards the positive field direction and produces current in the metallic rod.

If 'E' is the electric field intensity and 'm' is the mass of the electron, then

Force experienced by the electron $F = eE$ -----(1)

According to the Newton's second law $F = ma$ -----(2)

Equating (1) and (2)

$$eE = ma$$

$$a = \frac{eE}{m} \text{ -----(3)}$$

Due to the applied electric field, the electron gains acceleration 'a'

UNIT-2 Electrical and Magnetic Properties of materials

$$\text{Acceleration} = \frac{\text{Velocity}}{\text{Time}} = \frac{\text{Drift velocity}}{\text{Relaxation time}}$$
$$a = \frac{v_d}{\tau}$$

$$v_d = a\tau \text{ -----(4)}$$

Substituting (3) in (4)

$$v_d = \frac{eE}{m} \tau \text{ -----(5)}$$

If 'n' is the free electron density and 'e' is the charge of electron then current density is given by

$$J = nV_d e \text{ -----(6)}$$

Sub (5) in (6)

$$J = ne \left(\frac{eE}{m} \tau \right)$$

$$J = \frac{ne^2 E}{m} \tau \text{ -----(7)}$$

According to ohm's law, current density (J) is expressed as $J = \sigma E$ $\frac{J}{E} = \sigma$

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

$$\sigma = \frac{ne^2}{m} \tau \text{ -----(8)}$$

Thus the above equation represents the electrical conductivity of metal.

Thermal conductivity of a metal:

In general, the thermal conductivity takes place not only by thermal motion of free electrons but also by thermally excited lattice vibrations called phonons. The total thermal conductivity K_{tot} is given by

$$K_{\text{Tot}} = K_{\text{electron}} + K_{\text{Phonon}}$$

In metals, conductivity due to free electrons is predominant. $K_{\text{Tot}} \approx K_{\text{electron}}$

In insulators thermal conductivity is due to atomic or molecular vibrations of the lattice is predominant

$$\therefore K_{\text{Tot}} \approx K_{\text{phonon}}$$

In semiconductors both electron & phonon will contribute for thermal conduction.

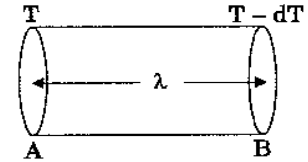
$$\therefore K_{\text{Tot}} \approx K_e + K_{\text{ph}}$$

Definition: Thermal conductivity of the material is defined as the amount of heat conducted per unit area per unit time maintained at unit temperature gradient

UNIT-2 Electrical and Magnetic Properties of materials

$$K = \frac{Q}{tA \left(\frac{dT}{dx} \right)} \text{ W/m/K}$$

Derivation: Let us consider a uniform rod AB with Temp (Hot) T at end A & T-dT (cold) at end B. Heat flows from hot end to cold end and the distance between A & B is λ . The no of conduction electrons in a metal is 'n' their average velocity is v.



At A, Average kinetic energy of an electron = $\frac{3}{2}KT$ -----(1)

At B, Average kinetic energy of an electron = $\frac{3}{2}K(T - dT)$ -----(2)

The number of electrons crossing per unit area per unit time is $\frac{1}{6} nv$

$$\begin{aligned} \text{Excess of kinetic energy carried by the electron from A to B} &= \left[\frac{3}{2}KT - \frac{3}{2}K(T - dT) \right] \frac{1}{6} nv \\ &= \left[\frac{3}{2}KT - \frac{3}{2}KT + \frac{3}{2}KdT \right] \frac{1}{6} nv \\ &= \frac{1}{4}nvKdT \text{ -----(3)} \end{aligned}$$

Similarly the deficient of kinetic energy carried by the electron from A to B per unit area in unit time = $-\frac{1}{4}nvKdT$ -----(4)

Hence, the net amount of energy transferred from A to B per unit area per unit time

$$\begin{aligned} Q &= \left(\frac{1}{4}nvKdT \right) - \left(-\frac{1}{4}nvKdT \right) \\ Q &= \frac{1}{2}nvKdT \text{ -----(5)} \end{aligned}$$

From basic definition of thermal conductivity

The amount of heat conducted per unit time per unit area is $Q = K \frac{dT}{\lambda}$ -----(6)

Equate (5) and (6) we get, $\frac{1}{2}nvKdT = K \frac{dT}{\lambda}$

$$K = \frac{1}{2}nvk\lambda \text{ -----(7)}$$

For metals

Relaxation time (τ) = Collision time (τ_c)

$$\tau v = \lambda \text{ -----(8)}$$

Sub (8) in (7) we get

$$K = \frac{1}{2}nv^2k\tau \text{ -----(9)}$$

This is the classical expression for thermal conductivity of a metal.

Weidemann-Franz law:

It states that for the metals, the ratio of thermal conductivity to electrical conductivity is directly proportional to the absolute temperature. This ratio is constant for all metals at a given temperature.

$$\frac{K}{\sigma} \propto T \quad \frac{K}{\sigma} = LT$$

Where, L is a constant known as Lorentz number.

UNIT-2 Electrical and Magnetic Properties of materials

We know that,

Electrical conductivity of a metal $\sigma = \frac{ne^2}{m} \tau$ ----- (1)

Thermal conductivity of a metal $K = \frac{1}{2} nv^2 k \tau$ ----- (2)

$$\frac{K}{\sigma} = \frac{\frac{ne^2}{m} \tau}{\frac{1}{2} nv^2 k \tau} \quad \frac{K}{\sigma} = \frac{1}{2} \frac{mv^2 k}{e^2} \text{ ----- (3)}$$

We know that the kinetic energy of an electron $\frac{1}{2} mv^2 = \frac{3}{2} kT$ ----- (4)

Substituting equation (4) in equation (3), we have $\frac{K}{\sigma} = \frac{3}{2} kT \frac{k}{e^2}$
 $\frac{K}{\sigma} = \frac{3}{2} \frac{k^2}{e^2} T$
 $\frac{K}{\sigma} = LT \text{ ----- (5)}$

where $L = \frac{3}{2} \frac{k^2}{e^2}$ is a constant and it is known as Lorentz number.

Thus it is proved that, the ratio of thermal conductivity to electrical conductivity of a metal is directly proportional to the absolute temperature of the metal. Weidemann -Franz law clearly shows that if a metal has high thermal conductivity, it will also have high electrical conductivity.

Lorentz number:

The ratio of thermal conductivity (K) of a metal to the product of electrical conductivity (σ) of a metal and absolute temperature (T) of the metal is a constant. It is called Lorentz number and it is given by $L = \frac{K}{\sigma T}$

The value of L can be calculated from the expression $L = \frac{3}{2} \frac{k^2}{e^2}$

$$L = \frac{3}{2} \frac{(1.38 \times 10^{-23})^2}{(1.6 \times 10^{-19})^2}$$

$$L = 1.12 \times 10^{-8} \text{ W } \Omega \text{ K}^{-2} \text{ (By theory)}$$

$$L = 2.44 \times 10^{-8} \text{ W } \Omega \text{ K}^{-2} \text{ (By Experiment)}$$

This discrepancy in the experimental and theoretical value of Lorentz number is one of the drawbacks of classical theory. It is rectified in quantum theory.

Merits of classical free electron theory

- It is used to verify ohm's law.
- The electrical and thermal conductivities of metals can be explained by this theory.
- It is used to derive Wiedemann-Franz law.
- It is used to explain the optical properties of metals.

UNIT-2 Electrical and Magnetic Properties of materials

Drawbacks of classical free electron theory

- It is a macroscopic theory
- Classical theory states that all the free electrons will absorb energy, but quantum theory states only few electrons will absorb energy.
- This theory cannot explain the Compton, photo-electric effect, paramagnetic, ferromagnetism, etc.
- The theoretical and experimental values of specific heat and electronic specific heat are not matched.
- The Lorentz number by classical theory does not have good agreement with the experimental value and it is rectified by quantum theory.
- According to this theory, the ratio $\frac{K}{\sigma T}$ is constant at all temperatures. But it is found that it is not constant at low temperatures.
- By this theory, the value of specific heat of a metal is $4.5R$, but the experimental value is $3R$, where R is a universal gas constant.
- The susceptibility of a paramagnetic material is inversely proportional to temperature. But experimental result shows that Para magnetism of a metal is independent of temperature. Moreover Ferromagnetism cannot be explained by this theory.

Differences between electrical and thermal conductivity

S. No	Electrical Conductivity	Thermal Conductivity
1	Electrical conductivity is based on the no of free electrons	Thermal conductivity is based both on electrons and phonons
2	The quantity of electrical charges flowing per unit time across unit area in the metal for unit applied electric field is called electrical conductivity	It is defined as the amount of heat conducted per unit time through the metal having unit area of cross section maintaining at unit temperature gradient between the two ends
3	Electrical conductivity takes place from higher potential side to lower potential side	Thermal conductivity takes place from hot end to cold end.
4	Unit : $\Omega^{-1} \text{ m}^{-1}$	Unit : $\text{W m}^{-1} \text{ K}^{-1}$

Quantum free electron theory:

In order to remove the failures of classical free electron theory, **Sommerfield** proposed quantum free electron theory in 1928, based on the quantum concepts.

According to this theory, the **electrons in a metal move in a constant potential**. He derived an expression for electron energies by using Schrodinger's wave equation and De- Broglie concept of matter waves. He treated the problem quantum mechanically using Fermi – Dirac statistics.

UNIT-2 Electrical and Magnetic Properties of materials

Important assumptions:

- ✓ The potential of an electron is uniform or constant within the crystal.
- ✓ The electrons possess wave nature.
- ✓ The allowed energy levels of an electron are quantized.
- ✓ The electrons have freedom to move within the crystal itself and they are restricted from leaving crystal due to potential barrier at its surface.
- ✓ The free electrons obey Fermi – Dirac statistics.

Merits of quantum free electron theory:

It explains the electrical conductivity, thermal conductivity and specific heat capacity of metals, photoelectric effect, Compton Effect etc.

Demerits of quantum free electron theory:

- ✓ It fails to provide the distinction between metals, semiconductors and insulators.
- ✓ It fails to explain the positive value of Hall co- efficient and some transport properties of metals.

Tunnelling

In quantum mechanics a particle having lesser energy (E) than the barrier potential (V) can easily cross over the potential barrier having a finite width ' l ' even without climbing over the barrier by tunnelling through the barrier. This process is called tunnelling.

Explanation: let us consider a beam of particles having kinetic energy E , less than the barrier potential (V), incident from region 1. According to classical mechanics the probability for the incident particles to cross the barrier is zero, because it has very less energy (E) when compared to the barrier potential (V).

But according to quantum mechanics, the incident wave from region (1) having the wave function Ψ_1 can cross the barrier region (2) by the process of tunnelling, represented by the wave function Ψ_2 and comes out to the region (3), represented by the wave function Ψ_3 . However based on the width of the potential barrier there is a probability for the wave, represented by the wave function Ψ_1 , to get reflected within the same region (1). The value of transmission coefficient T depends on the mass of the particle (m), thickness of the barrier (l) and the energy difference i.e, ($V - E$).

Examples

1. The tunnelling effect is observed in Josephson junction, in which electron pairs in the superconductor's tunnel through the barrier layer, giving rise to the Josephson current.
2. This effect is also observed in the case of emission of alpha particles by radioactive nuclei. Here, though the ' α ' particle has very less kinetic energy they are able to escape from the nucleus whose potential wall is around 2.5 MeV high.
3. Tunnelling also occurs in certain semiconductor diodes called tunnel diodes.
4. Electron tunnels through insulating layer and act as a switch by tunnelling effect.

UNIT-2 Electrical and Magnetic Properties of materials

Degenerate states: For various combinations of quantum numbers ‘n’ if we get the same Eigen value (Energy levels) but different Eigen functions, then it is called degenerate state.

The energy of the particle in a 3-dimensional in the ground state is given by

$$E_{n_x n_y n_z} = \frac{(n_x^2 + n_y^2 + n_z^2)h^2}{8ma^2}$$

Example: For three combination of quantum numbers say (112), (121) and (211), we get same energy values i.e., $E_{112} = E_{121} = E_{211} = \frac{6h^2}{8ma^2}$ but different Eigen functions i.e., $\Psi_{112} \neq \Psi_{121} \neq \Psi_{211}$

$$\psi_{112} = \sqrt{\frac{8}{a^3}} \sin \frac{\pi x}{a} \sin \frac{\pi y}{a} \sin \frac{2\pi z}{a} \quad \psi_{121} = \sqrt{\frac{8}{a^3}} \sin \frac{\pi x}{a} \sin \frac{2\pi y}{a} \sin \frac{\pi z}{a} \quad \psi_{211} = \sqrt{\frac{8}{a^3}} \sin \frac{2\pi x}{a} \sin \frac{\pi y}{a} \sin \frac{\pi z}{a}$$

Fermi Distribution Function

Fermi function $F(E)$ represents the probability of an electron occupying a given energy state at absolute temperature. The energy distribution of the particles was found by Fermi – Dirac statistics. Fermi- Dirac Statistics deals with the energy distribution of the particles having half integral spin values called as Fermions or Fermi particles. Example: Electrons.

The Fermi distribution is given by $F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$

Where,

E	:	Energy of the energy level whose occupancy is being considered.
E_F	:	Energy of the Fermi level (Fermi energy)
k	:	Boltzmann’s constant
T	:	Absolute temperature

The probability value $F(E)$ lies between 0 and 1.

If $F(E) = 1$, the energy level is occupied by an electron.

If $F(E) = 0$, the energy level is vacant.

If $F(E) = 0.5$, then there is 50% chance for the electron to occupy the given energy level.

Effect of temperature on Fermi function:

The effect of temperature on Fermi function $F(E)$ can be discussed with respect to the above equation.

Case (1) : Probability of occupation for $E < E_F$ at $T = 0$

$$F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

When $T = 0$ and $E < E_F$, we have

$$F(E) = \frac{1}{1 + e^{(-ve)/0}} \quad F(E) = \frac{1}{1 + 0}$$

$$F(E) = \frac{1}{1 + e^{-\infty}} \quad F(E) = 1$$

UNIT-2 Electrical and Magnetic Properties of materials

Thus at $T = 0$, there is 100% chance for the given energy level to be filled with electrons. It can also be said that the energy levels below the Fermi energy levels are filled with electrons.

Case (2) : Probability of occupation for $E > E_F$ at $T = 0$

$$F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

When $T = 0$ and $E > E_F$, we have

$$F(E) = \frac{1}{1 + e^{(+ve)/0}}$$

$$F(E) = \frac{1}{1 + \infty}$$

$$F(E) = 0$$

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

$$F(E) = \frac{1}{\infty}$$

Thus at $T = 0$, there is 0% chance for the given energy level to be filled with electrons. It can also be said that the energy levels above the Fermi energy level are not occupied by the electrons.

Case (3): Probability of occupation for $E = E_F$ at $T > 0K$

$$F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

When $T = 0$ and $E = E_F$, we have

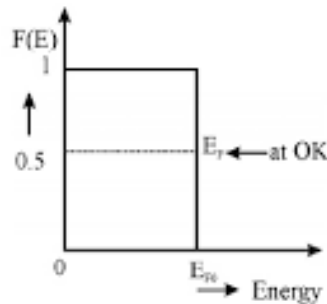
$$F(E) = \frac{1}{1 + e^0}$$

$$F(E) = \frac{1}{2}$$

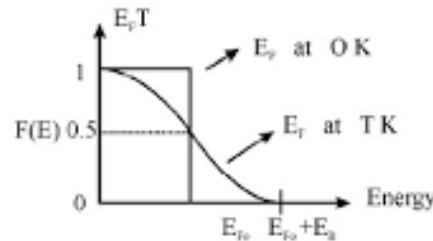
$$F(E) = \frac{1}{1 + 1}$$

$$F(E) = 0.5$$

Here, there is 50% chance for the electrons to occupy Fermi energy level i.e., the value of $F(E)$ becomes 0.5 at $E = E_F$



(a) At $T=0K$



(b) at $T>0K$

Case (4): Probability of occupation at any temperature

When the temperature is raised slowly from absolute zero, the Fermi distribution function smoothly decreases to zero. Due to the supply of thermal energy the electrons within the range of kT below the Fermi level alone takes the energy $\approx kT$ and goes to higher energy state. Hence at any temperature (T), empty states will also be available below E_F . Therefore the fermi distribution reduces to classical Maxwell Boltzmann statistics.

UNIT-2 Electrical and Magnetic Properties of materials

Uses of Fermi distribution function:

- It gives the probability of occupation for a given energy level at a given temperature.
- It gives the idea about filled and unfilled states.
- It is very useful in the calculation of number of free electrons per unit volume at given temperature.
- It is very useful in the calculation of Fermi energy of a metal.

Density of states

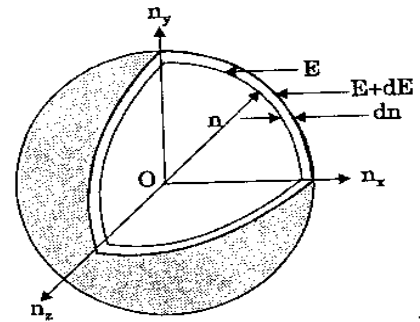
The Fermi function gives only the probability of filling up of electrons in a given energy state, it does not give information about the number of electrons that can be filled in a given energy state. To know that we should know about the number of available energy states so called density of states.

Definition:

It is defined as the number of available electron states per unit volume in an energy interval E and $E+dE$. It is denoted by $Z(E)$ and it is given by

$$Z(E)dE = \frac{\text{Number of energy states in the energy interval } E \text{ and } E + dE}{\text{Volume of the metal piece}}$$

Derivation: Let us consider a cubical sample with side 'a'. A sphere is constructed with three quantum numbers n_x , n_y and n_z as coordinate axes in three-dimensional space. A radius vector n is drawn from the origin 'o' to a point with coordinates n_x , n_y and n_z in this space. All the points on the surface of that sphere will have the same energy E . thus $n^2 = n_x^2 + n_y^2 + n_z^2$ denotes the radius of the sphere with energy E . This sphere can be further divided into many shells. Each shell represents a particular combination of quantum numbers. Therefore it denotes a particular energy value with a particular radius. In this space, unit volume represents one energy state.



Number of energy states within a sphere of radius 'n' = $\frac{4}{3}\pi n^3$ ----- (1)

UNIT-2 Electrical and Magnetic Properties of materials

Since the quantum numbers can have only positive integer values; we have to take only one octant of the sphere, i.e., $\frac{1}{8}$ th of the spherical volume. Therefore the number of available energy states within one octant of the sphere of radius 'n' corresponding to energy E is

$$= \frac{1}{8} \left[\frac{4}{3} \pi n^3 \right] \text{-----(2)}$$

Similarly, the number of available energy states within one octant of the sphere of radius 'n+dn' corresponding to energy E+dE is $= \frac{1}{8} \left[\frac{4}{3} \pi (n + dn)^3 \right] \text{-----(3)}$

Now, the number of available energy states between the shell of radius n and n+dn is determined by subtracting eqn (2) from eqn (3)

$$\begin{aligned} N(E)dE &= \frac{1}{8} \left(\frac{4\pi}{3} \right) (n + dn)^3 - \frac{1}{8} \left(\frac{4\pi}{3} \right) n^3 \\ &= \frac{1}{8} \left(\frac{4\pi}{3} \right) [(n + dn)^3 - n^3] \\ N(E)dE &= \left(\frac{\pi}{6} \right) [n^3 + dn^3 + 3n^2dn + 3ndn^2 - n^3] \end{aligned}$$

Since dn is very small, higher powers of dn terms dn^2 and dn^3 can be neglected.

$$\begin{aligned} N(E)dE &= \left(\frac{\pi}{6} \right) [3n^2dn] \\ N(E)dE &= \left(\frac{\pi}{2} \right) [n^2dn] \\ N(E)dE &= \left(\frac{\pi}{2} \right) n[ndn] \text{-----(4)} \end{aligned}$$

We know that the energy of the electron in a cubical metal piece of sides 'a' is given by

$$E = \frac{n^2 h^2}{8ma^2} \text{-----(5)}$$

$$n^2 = \left[\frac{8ma^2 E}{h^2} \right] \text{-----(6)}$$

$$n = \left[\frac{8ma^2 E}{h^2} \right]^{1/2} \text{-----(7)}$$

Differentiating eqn(6) we get $ndn = \left[\frac{8ma^2 dE}{2h^2} \right] \text{----- (8)}$

Substituting eqns (7) and (8) in eqn (4), we have

$$\begin{aligned} N(E)dE &= \frac{\pi}{2} \left[\frac{8ma^2 E}{h^2} \right]^{1/2} \left[\frac{8ma^2 dE}{2h^2} \right] \\ N(E)dE &= \frac{1}{2} \frac{\pi}{2} \left[\frac{8ma^2 E}{h^2} \right]^{1/2} \left[\frac{8ma^2 dE}{h^2} \right] \\ N(E)dE &= \frac{\pi}{4} \left[\frac{8ma^2}{h^2} \right]^{1/2} E^{1/2} \left[\frac{8ma^2}{h^2} \right] dE \text{-----(9)} \\ N(E)dE &= \frac{\pi}{4} \left[\frac{8ma^2}{h^2} \right]^{3/2} E^{1/2} dE \text{-----(10)} \end{aligned}$$

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Pauli's exclusion principle states that two electrons of opposite spins can occupy each state and hence the number of energy states available for electron occupancy is given by

$$\begin{aligned}N(E)dE &= 2 \times \frac{\pi}{4} \left[\frac{8ma^2}{h^2} \right]^{3/2} E^{1/2} dE \\N(E)dE &= \frac{\pi}{2} \left(\frac{a}{h} \right)^3 (8m)^{3/2} E^{1/2} dE \\N(E)dE &= \frac{\pi}{2} \left(\frac{a}{h} \right)^3 8(2m)^{3/2} E^{1/2} dE \\N(E)dE &= \frac{4\pi}{h^3} (2m)^{3/2} a^3 E^{1/2} dE \text{ -----(11)}\end{aligned}$$

Density of the states is given by the number of energy states per unit volume.

$$\begin{aligned}Z(E)dE &= \frac{N(E)dE}{V} \\Z(E)dE &= \left[\frac{\frac{4\pi}{h^3} (2m)^{3/2} a^3 E^{1/2} dE}{a^3} \right] \\Z(E)dE &= \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} dE \text{ -----(12)}\end{aligned}$$

This is the expression for the density of charge carriers in the energy interval E and $E+dE$. It is used to calculate the carrier concentration in metals and semiconductors.

Carrier concentration

Carrier concentration, i.e., the number of electrons per unit volume in a given energy interval is calculated by summing the product of the density of the state's $Z(E)$ and the occupancy probability $F(E)$.

i.e.,
$$n_c = \int Z(E)F(E)dE$$

Substituting the expressions for $Z(E)$ and $F(E)$, we have

$$n_c = \int \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} \frac{1}{1 + e^{(E-E_F)/kT}} dE \text{ -----(13)}$$

For a metal at absolute zero temperature, the upper most occupied level is E_F and all the levels are completely filled below E_F .

For a material at absolute zero $F(E) = 1$.

$$\begin{aligned}n_c &= \int \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} E^{\frac{1}{2}} dE \text{ -----(14)} \\n_c &= \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} \int_0^{E_F} E^{\frac{1}{2}} dE \\&= \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} \left(\frac{E^{\frac{3}{2}}}{\frac{3}{2}} \right)_0^{E_F} \\&= \frac{2}{3} \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} E_F^{\frac{3}{2}}\end{aligned}$$

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$$n_c = \frac{8\pi}{3h^3} (2m)^{\frac{3}{2}} E_{F0}^{\frac{3}{2}} \text{ -----(15)}$$

This eqn is used to calculate the carrier concentration in metals and semi conductors.

Expression for Fermi energy at 0K:

We know $n_c = \frac{8\pi}{3h^3} (2m)^{\frac{3}{2}} E_{F0}^{\frac{3}{2}}$

$$E_{F0}^{\frac{3}{2}} = \frac{3n_c}{8\pi} \left(\frac{h^2}{2m} \right)^{\frac{3}{2}}$$

$$E_{F0} = \left(\frac{3n_c}{8\pi} \right)^{\frac{2}{3}} \left(\frac{h^2}{2m} \right) \text{ -----(16)}$$

This eqn is used to find out the Fermi energy of metals and semiconductors.

Average Energy of an electron at 0K

$$\text{Average Energy of an electron at 0K } E_{Avg} = \frac{\text{Total energy of electrons at 0K } (E_{tot})}{\text{Number of energy states at 0K } (N(E)dE)}$$

Here, the Total energy of electrons at 0K $(E_{tot}) =$

$$\text{Average Energy of an electron at 0K } \times \text{ Number of energy states at 0K } (N(E)dE)$$

$$E_{tot} = \int_0^{E_F} N(E)dE \cdot E$$

$$E_{tot} = \int_0^{E_{F0}} \frac{4\pi}{h^3} (2m)^{3/2} E_F^{1/2} dE \cdot E$$

$$E_{tot} = \int_0^{E_{F0}} \frac{4\pi}{h^3} (2m)^{3/2} E_F^{3/2} dE$$

$$E_{tot} = \frac{4\pi}{h^3} (2m)^{3/2} \frac{E_{F0}^{5/2}}{5/2}$$

$$E_{tot} = \frac{8\pi}{5h^3} (2m)^{3/2} E_{F0}^{5/2} \text{ -----(1)}$$

We know $N(E)dE = \frac{8\pi}{3h^3} (2m)^{\frac{3}{2}} E_{F0}^{\frac{3}{2}} \text{ ----- (2)}$

$$E_{Avg} = \frac{\frac{8\pi}{5h^3} (2m)^{3/2} E_{F0}^{5/2}}{\frac{8\pi}{3h^3} (2m)^{\frac{3}{2}} E_{F0}^{\frac{3}{2}}}$$

$$E_{Avg} = \frac{3}{5} E_{F0}$$

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ELECTRONS IN PERIODICAL POTENTIAL

The free electron theory explains the properties of thermal conductivity, electrical conductivity and specific heat of most of the metals. But, it fails to explain why some solids are conductors, some are insulators and others are semiconductors.

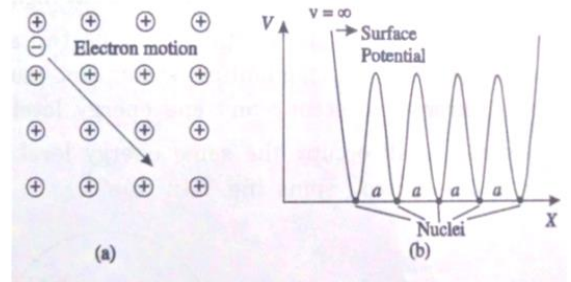
A solution to this problem was given by band theory of solids and is called zone theory.

According to free electron theory, the potential energy of the electron inside the crystal through which an electron moves is supposed to be (zero). So it is completely free to move about in the crystal, restrained only by the surface of the crystal.

Postulates

1. According to band theory, potential energy of electron within the crystals is periodic due to periodicity of the crystal i.e., free electron move inside periodic lattice field.
2. The potential energy of the solid of the solid varies periodically with the periodicity of space lattice 'a' which is nothing but interatomic spacing.

Inside a real crystal, the electrons (-) move through periodic arrangement of positively charged holes (+) as shown in the fig(a). Fig.(b) shows one dimensional periodic potential distribution for a crystal. It is assumed that the potential energy of the electron at the positive ion site is zero and is maximum when it is half way between the adjacent nuclei.



ENERGY BANDS IN SOLIDS

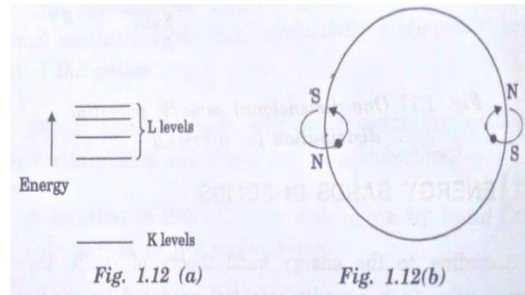
According to the energy band theory of solids, the free electrons move in a periodic potential produced by positive ion cores. The electrons are treated as weakly perturbed by the periodic potential. A simple qualitative explanation of the formation of energy bands in a solid is given below.

A solid contains an enormous number of atoms packed closely together. Each atom when isolated has a discrete set of electron levels, 1s, 2s, 2p, ... If we imagine the N atoms on the solid to be isolated from one another, they would have completely coinciding schemes of energy levels.

The energies of electrons within any one isolated atom obey the following conditions.

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- (i) There are specific electronic energy levels in each atom (fig. a). Electrons cannot occupy space between these levels
- (ii) Electrons fill the lowest energy levels first. A specific quantity of energy, called a quantum of energy must be supplied to move an electron to the next higher level.
- (iii) Pauli's, exclusion principle states that no two electrons can occupy the same quantum state. Not more than two electrons can occupy any one energy level. Two electrons shall occupy the same energy level because they have opposite electron spins (fig b).

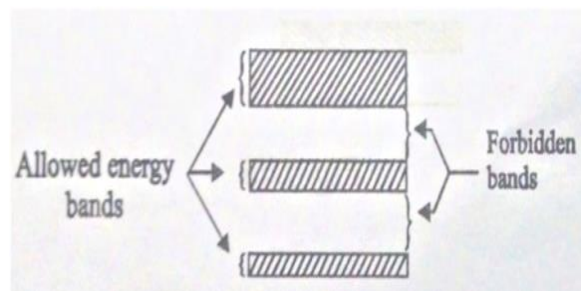
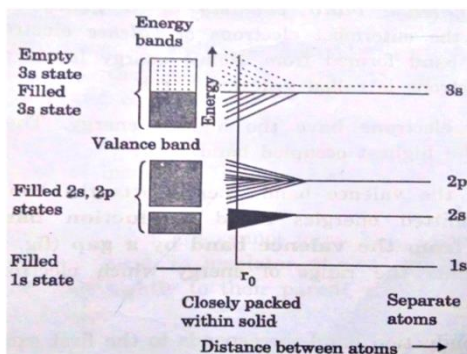


When the atoms are brought in close proximity to form a solid, the valence electrons of common to the entire crystal, and their outermost electronic orbits overlap. Therefore, N electrons will now have to occupy different energy levels, which may be brought about by the electric forces exerted on each electron by all N nuclei. As a result of these forces, each atomic energy level is split up into a large number of closely spaced energy levels. **A set of such closely spaced energy levels is called an energy band.**

Consider 11 electrons of a neutral sodium atom, each occupying specific energy level as indicated in fig. The energy levels of sodium become bands when the atoms lie close together.

In an energy band, allowed energies are almost continuous. These energy bands are separated by ranges of energies that have no allowed energy levels. These regions are known as **forbidden bands** or **energy gaps**.

The amount of splitting is not the same for different levels. The levels filled by valence electrons are disturbed to a greater extent, while this filled by electrons of inner shells are distributed only slightly. If there are N atoms in a solid, there are N allowed quantum states in each band. Each quantum state is occupied by a maximum of two electrons with opposite spins. Thus, each energy band can be occupied by $2N$ electrons.



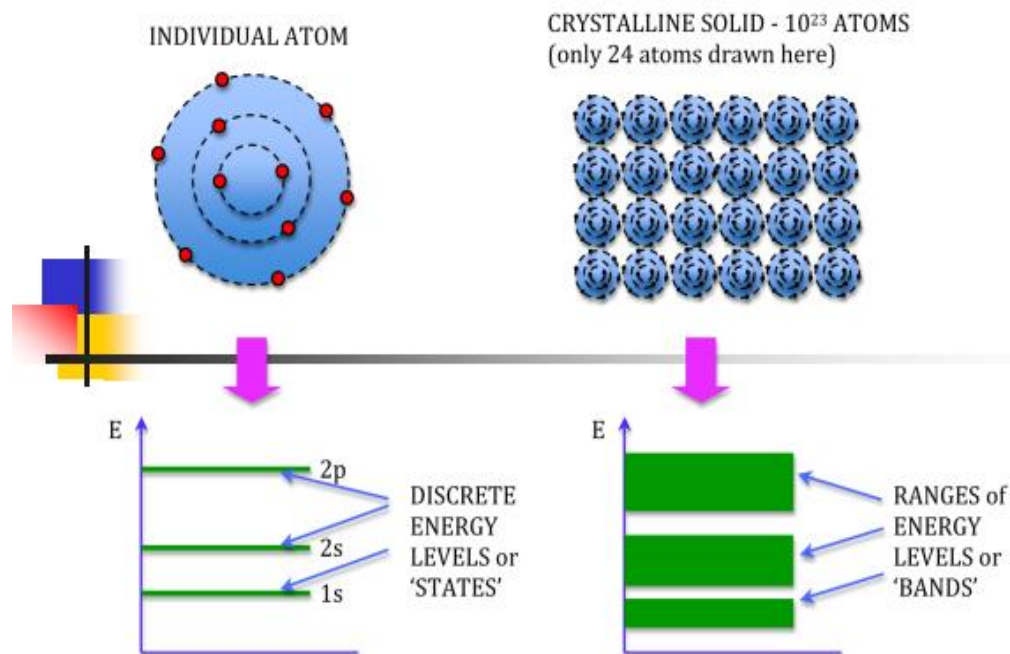
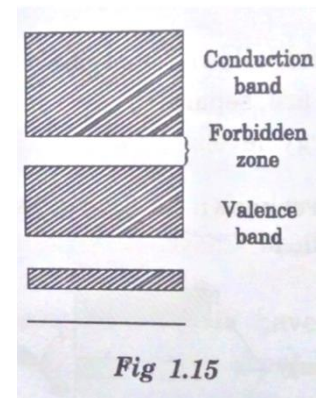
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The **valence band** consists of a group of states containing the outermost electrons or valence electrons of an atom. The band formed from atomic energy levels contains valence electrons is called **valence band**. These electrons have the highest energy. The band is obviously the highest occupied band.

Above the valence band, there exists the band of next higher permitted energies called **conduction band**. It is separated from the valence band by a **gap**. The gap represents the range of energy which electrons cannot possess.

The conduction band corresponds to the first excited states and it is normally the lowest unfilled energy band. In conduction band, the electrons can move freely and they are generally called **conduction electrons**.

According to free electron theory, the potential energy of the electron inside the crystal through which an electron moves is supposed to be constant which an electron moves is supposed to be constant (zero) and so it is completely free to move throughout the crystal, restrained only by the surface of the crystal.



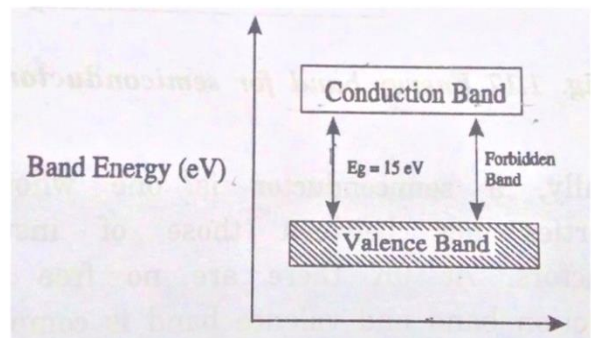
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Classification of Metals, Semiconductors and Insulators

On the basis of width of forbidden gap valence and conduction band the solids are classified into insulators, semiconductors and conductors.

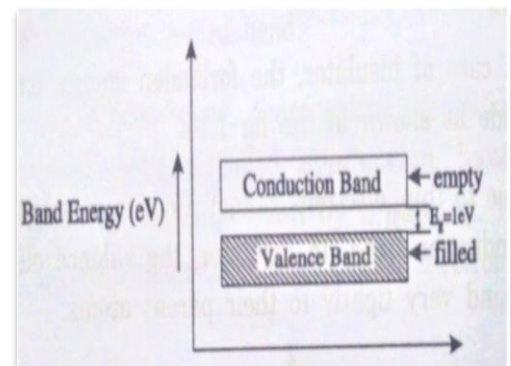
Insulators

- In case of insulator, the forbidden energy band is very wide as shown in the fig. Due to this, electrons cannot jump from valance band to conduction band. In insulator, the valance electrons are bound very tightly to their parent atoms.
- For example, In the case of material like Glass, the valance band is completely full at 0k and the energy gap between valance band and conduction band of the order of 10eV.
- Even in the presence of high electric field, the electrons cannot jump from the valance band to conduction band.
- When a very large energy is supplied, an electron may jump across the forbidden gap. Increase in temperature also enables some electrons to go the conduction band.
- **This explains why certain insulators became conductors at high temperature.** The resistivity of insulators is of the order of $10^7 \Omega\text{m}$. (ohmmeter)



Semiconductor

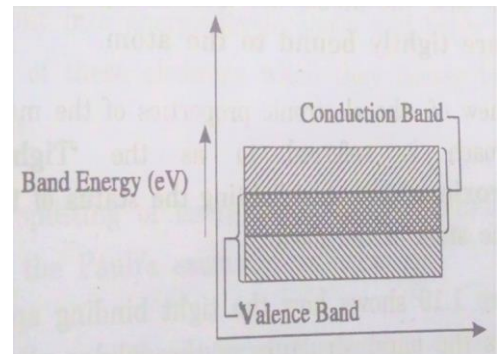
- In semiconductors, the forbidden gap is very small as shown in the fig. Germanium and silicon are the best example semiconductors.
- In germanium, the forbidden gap is of the order of 0.7 eV while in case of silicon, it is the order of 1.1eV.
- Actually, a semiconductor one whose electrical property lies between those of insulators and conductors. At 0k there are no free electrons in conduction band and valence band is completely filled.
- When a small amount of energy is supplied, the electrons can easily jump from valence band to conduction, since the forbidden gap is very small.
- In semiconductors, the conductivities is the order of $10^2 \Omega\text{m}$. (ohm meter)



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Conductor

- In case of conductors, there is no forbidden gap both conduction band and valence band overlap each other as shown in the fig.
- In conduction gap, plenty of free electrons available for the process of electric conduction. The electron from the valence band enters into the conduction band.
- The most important fact in conductor is that due to the absence of forbidden gap, there is no structure to establish holes. The total current in conductor is simply the flow of electrons.

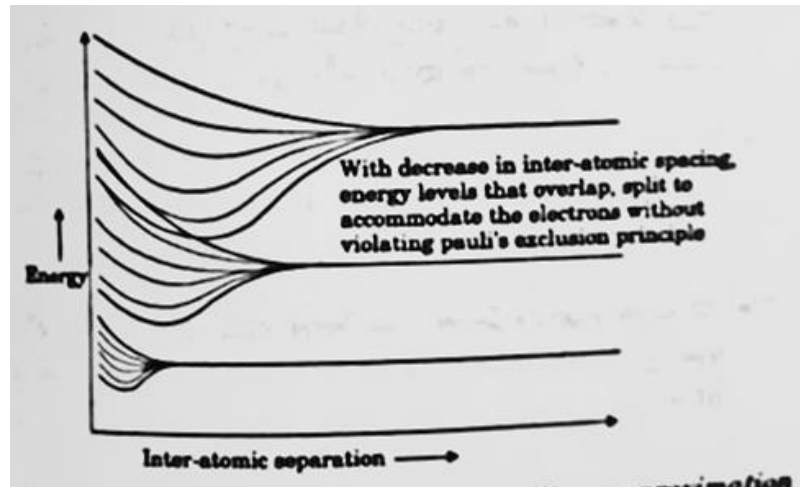


Tight binding approximation

There are usually two approaches to understand the origin of band theory associated with solids. One is the “nearly free electron model” and the other “tight-binding model”.

- 1) Nearly free electron model: In the nearly free electron approximation, interactions between electrons are completely ignored. In solids there exists the ionic core which are tightly bound to the lattice location, while the free electrons are free to move here and there throughout the solid.
- 2) Tight-binding model: The opposite extreme to the nearly-free electron model assumes the electrons in the crystal behave much like an assembly of constituent atoms.
 - In this approach, the atoms are independent to begin with and they are brought together to build the solid. The electrons are bound to their respective individual atoms to begin with.
 - The atoms are free to begin while the electrons are tightly bound to the atom.
 - When atoms are far apart all the bound electrons have fixed energy levels.
 - When the atoms are brought close to form a solid, the electrons will maintain their original energy levels as long as interatomic separation is large.
 - When atoms are close enough the outer shell electrons begin to overlap and the energy levels begin to split above and below the energy level of individual atoms.
 - Initially the outer shell electrons overlap and as the interatomic spacing keeps on decreasing further, the inner shell electrons overlap and hence the corresponding energy levels also split.

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Concept of Effective Mass

The mass of an electron in the periodic potentials of a crystal is different from the free electron mass and is usually referred to as the effective mass. Effective mass of an electron is the mass of the electron when it is accelerated in a periodic potential. It is denoted as m^* .

According to de Broglie hypothesis, a moving electron is associated with a wave. The velocity of an electron (v) is equal to the group velocity (v_g) of the associated wave.

The group velocity is given by
$$v_g = \frac{d\omega}{dk} \text{-----(1)}$$

Where ω is the angular frequency ($2\pi\nu$) and K is the propagation vector of the wave.

In quantum mechanics, the energy, ' E ' of an electron is given by $E = h\nu$

$$E = \frac{h\omega}{2\pi}$$

$$E = \hbar \omega$$

$$\omega = \frac{E}{\hbar} \text{-----(2)}$$

Substituting value of ω from eq (2) to eq (1), we get
$$v_g = \frac{d}{dk} \left(\frac{E}{\hbar} \right)$$

$$v_g = \frac{1}{\hbar} \frac{dE}{dk} \text{-----(3)}$$

Differentiating Equation (3) with respect to ' t ', we get acceleration of electron as

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$$a = \frac{d(v_g)}{dt}$$

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

$$a = \frac{1}{\hbar} \left(\frac{d^2E}{dk^2} \right) \frac{dk}{dt} \text{ -----(4)}$$

In quantum theory, the momentum of an electron is given by $p = \frac{h}{\lambda}$

$$p = \frac{h}{2\pi} \frac{2\pi}{\lambda}$$

$$p = \hbar k \text{ -----(5)}$$

Differentiating momentum with respect to t $\frac{dp}{dt} = \hbar \frac{dk}{dt}$

Since force acting on the electron $F = \frac{dp}{dt}$

$$F = \hbar \frac{dk}{dt} \quad \frac{dk}{dt} = \frac{F}{\hbar} \text{ -----(6)}$$

Substituting eqn (6) in (4) we get, $a = \frac{1}{\hbar} \left(\frac{d^2E}{dk^2} \right) \frac{F}{\hbar}$

$$a = \frac{1}{\hbar^2} \left(\frac{d^2E}{dk^2} \right) F$$

$$F = \left[\frac{\hbar^2}{\left(\frac{d^2E}{dk^2} \right)} \right] a \text{ -----(7)}$$

When an electric field is applied, acceleration of the electron due to this field

$$a = \frac{eE}{m^*} = \frac{F}{m^*}$$

$$F = m^* a \text{ -----(8)}$$

Comparing equations (7) and (8), we have $m^* a = \left[\frac{\hbar^2}{\left(\frac{d^2E}{dk^2} \right)} \right] a$

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

The above equation indicates the effective mass of an electron is not a constant, but depends on the value of $\left(\frac{d^2E}{dk^2} \right)$

Special cases

Case (1): If $\left(\frac{d^2E}{dk^2} \right)$ is positive, then m^* is also positive

Case (2): If $\left(\frac{d^2E}{dk^2} \right)$ is negative, then m^* is also negative

Case (3) If $\left(\frac{d^2E}{dk^2} \right)$ is large, then the electron behave as a light particle

Case (4) If $\left(\frac{d^2E}{dk^2} \right)$ is very small, then the electron behave as heavy particle

Concept of holes

- ❖ Effective mass plays an important role in conduction process of semiconductors & holes – full or filled valence bands.
- ❖ Effective mass is –ve near zone edges of filled valence bands.
- ❖ Electrons are accelerated in direction opposite to that the applied field direction – negative mass behavior of electrons.
- ❖ Electrons with negative effective mass is considered as a new entity having same positive mass as that of an electron but with a positive charge – hole
- ❖ Positive hole conduction and negative electron conduction are in equilibrium.

MAGNETIC MATERIALS

INTRODUCTION

Magnetism arises from the magnetic moment or magnetic dipole of the magnetic materials. When an electron revolves around the positive nucleus, orbital magnetic moment arises. Similarly when the electron spins, spin magnetic moment arises. Any material can be magnetized by an external magnetic field is called as magnetic materials. When a magnetic field is applied externally, the magnetic materials can be easily magnetized since they have permanent magnetic moment. Among the different types of magnetic materials, the following five will be having practical application.

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1. Dia magnetic materials
2. Para magnetic materials
3. Ferro magnetic materials
4. Anti Ferro magnetic materials
5. Ferrimagnetic materials etc.

BASIC TERMS AND DEFINITIONS

1. Magnetic dipole: Magnetic dipole is a system consisting of two equal and opposite magnetic poles separated by a small distance ' l '. Where ' l ' is the length of the magnet.

2. Magnetic moment: The product of magnetic pole strength ' m ' and the length of the magnet ' l ' is known as magnetic moment (M) $M = m.l$

3. Magnetic flux (ϕ): Total number of magnetic lines of forces passing through a surface is known as magnetic flux. It is represented by ϕ and its unit is weber (WB).

4. Magnetic induction (or) Magnetic Flux density: Magnetic induction is the number of magnetic force passing through unit area perpendicularly. $B = \frac{\phi}{A}$ Its unit is ' Wb/m^2 ' or *Tesla*.

5. Magnetic field intensity (or) Strength (H): It is defined as the force experienced by a unit North Pole placed at the given point in a magnetic field. Its unit is N/Wb or *Ampere/meter*.

6. Intensity of magnetization: Magnetization means the process of converting a Non-magnetic material into the magnetic material. It measures the magnetization of a magnetized specimen. It is defined as the magnetic moment per unit volume. $I = \frac{M}{V}$ Its unit is Wb/m^2

7. Magnetic permeability (μ): It is the ratio between magnetic flux density (B) and the magnetic field intensity (H). $\mu = \mu_0 \mu_r$ $\mu = \frac{B}{H}$

8. Relative permeability (μ_r): It is the ratio between permeability of the medium to the permeability of free space $\mu_r = \frac{\mu}{\mu_0}$

9. Magnetic Susceptibility, χ : It is the ratio between intensity of magnetization (I) and the magnetic field intensity (H) $\chi = \frac{I}{H}$

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Relation between μ_r and χ :

We know, $B = \mu H$

In other way $B = \mu_0(I + H)$

$$B = \mu_0 H \left(\frac{I}{H} + 1 \right)$$

$$\frac{B}{H} = \mu_0 (1 + \chi)$$

The relative permeability $\mu = \mu_r \mu_0$ and $\frac{B}{H} = \mu$

$$\mu_r \mu_0 = \mu_0 (1 + \chi)$$

$$\mu_r = 1 + \chi$$

Where χ is the Susceptibility of the medium.

ORIGIN OF MAGNETIC MOMENT AND BOHR MAGNETON

ORIGIN OF MAGNETIC MOMENT

Any matter is basically made up of atoms. The property of magnetism exhibited by certain materials with the magnetic property of its constituent atoms. We know that electrons in an atom revolve around the nucleus in different orbits.

Basically there are three contributions for the magnetic dipole moment of an atom.

1. The orbital motions of electrons (the motion of electrons in the closed orbits around the Nucleus) are called orbital magnetic moment.
2. Spin motion of the electrons (due to electron spin angular momentum) is called spin magnetic moment.
3. The contribution from the nuclear spin (due to nuclear spin angular momentum) is nearly 10^3 times smaller than that of electron spin; it is not taken into consideration.

BOHR MAGNETON: The magnetic moment contributed by an electron with angular momentum quantum number $n = 1$ is known as Bohr Magnetron.

$$\mu_B = \frac{eh}{4\pi m} \mu_B = 9.27 \times 10^{-24} \frac{A}{m^2}$$

CLASSIFICATION OF MAGNETIC MATERIALS:

(On the basis of magnetic moment)

Magnetic materials are basically divided into two types on the basis of magnetic moments, namely

1. Materials not having any permanent magnetic moment.

Examples: Dia-magnetic material

2. Materials having permanent magnetic moment

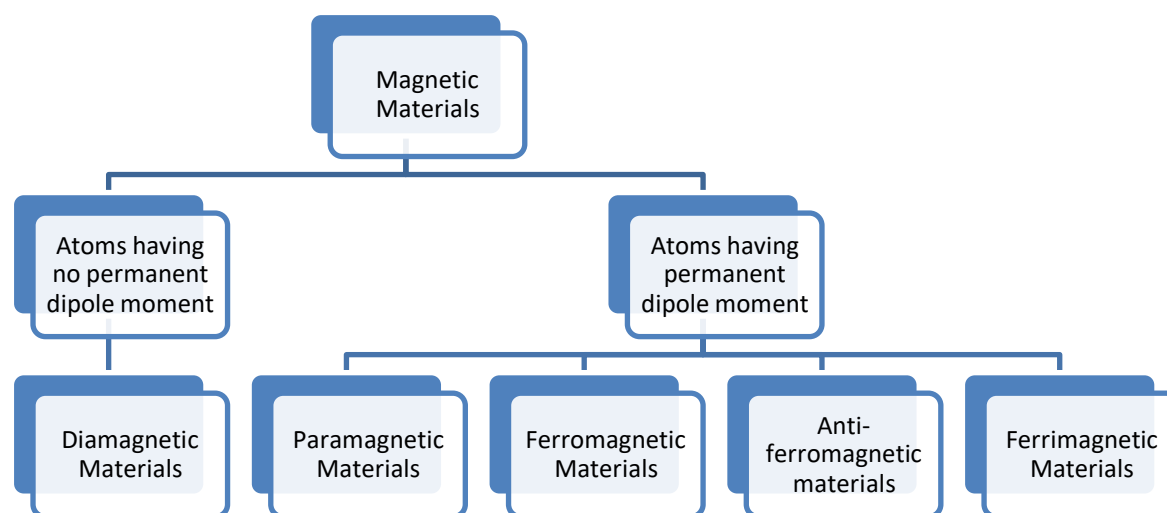
Examples: Para-magnetic materials

Ferro magnetic materials

Ferri magnetic materials

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Depending on the interaction between the induced dipoles, magnetic materials having permanent magnetic moment are classified into three.



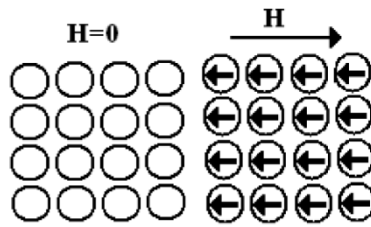
- If the permanent dipoles do not interact among themselves, the materials are known as ***paramagnetic materials***
- If the permanent dipole is strong and all the dipoles line up in parallel, the materials are known as ***Ferromagnetic materials***.
- If the permanent dipoles line up in anti parallel direction, the materials are known as antiferromagnetic or Ferrimagnetic materials.

DIAMAGNETIC MATERIALS:

Diamagnetism is exhibited by all the materials. The atoms in the diamagnetic materials do not possess permanent magnetic moment. However, when a material is placed in a magnetic field, the electrons in the atomic orbits tend to counteract the external magnetic field and the atoms acquire an induced magnetic moment. As a result, the material becomes magnetized. The direction of the induced dipole moment is opposite to that of externally applied magnetic field. Due to this effect, the material gets very weakly repelled, in the magnetic field. This phenomenon is known as diamagnetism.

When a magnetic field H_0 is applied in the direction shown in fig., the atoms acquire an induced magnetic moment in the opposite direction to that of the field. The strength of the induced magnetic moment is proportional to the applied field and hence magnetization of the material varies directly with the strength of the magnetic field. The induced dipoles and magnetization vanish as soon as the applied field is removed.

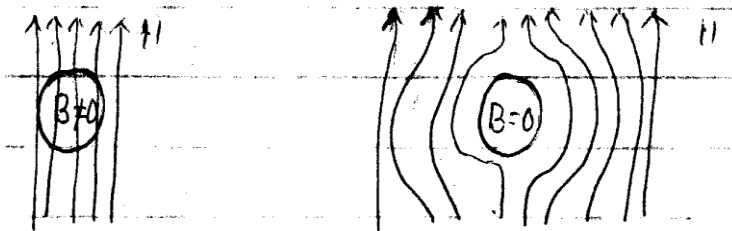
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Properties:

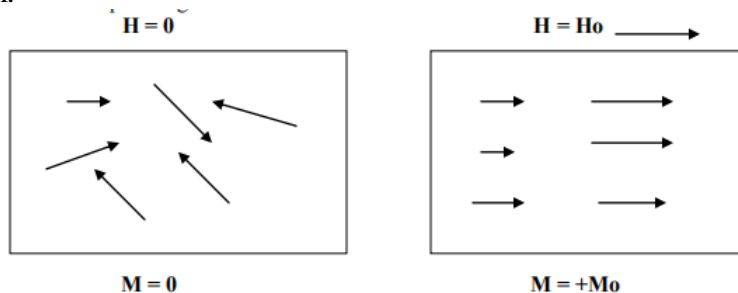
- Permanent dipoles are absent. Therefore the magnetic effects are very small.
- They repel the magnetic lines of force.
- The susceptibility is negative, and is independent of temperature and applied field.
- Permeability is less than unity.
- When temperature is less than critical temperature diamagnets become normal material

Examples: Gold, germanium, Silicon, water, alcohol, etc.



PARAMAGNETIC MATERIALS:

In certain materials, each atom or molecule possesses a net permanent magnetic moment (due to orbital and spin magnetic moment) even in the absence of an external magnetic field. The magnetic moments are randomly oriented in the absence of external magnetic field. Therefore the net magnetic moment is zero, and hence the magnetization of the material is zero. But, when an external magnetic field is applied, the magnetic dipoles tend to align themselves in the direction of the magnetic field and the material becomes magnetized. As shown in fig. This effect is known as paramagnetism.



Thermal agitation disturbs the alignment of the magnetic moments. With an increase in Temperature, the increase in thermal agitation tends to randomize the dipole direction thus leading to a decrease in magnetization. This indicates that the paramagnetic susceptibility decreases with increases in temperature. It is noted that the paramagnetic susceptibility varies inversely with temperature.

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$$\chi = \frac{C}{T}$$

This is known as Curie's law of paramagnetism and C is called Curie's constant.

Properties:

- The magnetic lines of force pass through the material.
- They have permanent magnetic dipoles.
- The susceptibility is positive and it depends on the temperature.
- Permeability is greater than one.
- When the temperature is less than critical temperature, the material becomes diamagnetic.



Examples: CuSO₄, MnSO₄, Platinum, aluminium, etc.

FERROMAGNETIC MATERIALS:

In ferromagnetic material the numbers of unpaired electrons are more. Most of the spin magnetic moment points in one direction. In the absence of magnetic field the dipoles align themselves parallel to each other and give rise to magnetic field called as *spontaneous magnetization*. When a small magnetic field is applied, the dipoles get reorient itself along the direction of the magnetic field and they become very strong magnets.



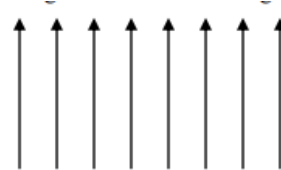
Properties:

- All the magnetic lines of force pass through the material, since it has its own magnetization.
- They have magnetization, even in the absence of external field.
- They have permanent magnetic dipoles.
- The susceptibility is positive and very high.

According to Curie Weiss law the susceptibility is given

by $\chi = \frac{C}{T - \theta}$

- Permeability is very much greater than 1
- When the temperature is greater than Curie temperature, they become paramagnetic.



COMPARISON OF DIAMAGNETIC, PARAMAGNETIC AND FERROMAGNETIC MATERIALS.

S.No	Dia magnetic materials	Paramagnetic materials	Ferromagnetic materials
1	In diamagnetic materials there are equal number of electron spins which are randomly oriented and hence the net magnetic moment is zero.	In paramagnetic materials there is unequal number of electron spins and hence there exists a permanent magnetic moment.	In ferromagnetic materials there is more number of unequal electron spins and hence there exists enormous amount of permanent magnetic moment.

UNIT-2 Electrical and Magnetic Properties of materials

2	When the external magnetic field is applied, the electrons will align perpendicular to the field direction and hence it reduces the magnetic induction present in the material. Thus they are named as weak magnets.	When the external magnetic field is applied, the electrons will align parallel to the field direction and hence the material is magnetized. Thus they are named as strong magnets.	When the external magnetic field is applied, the electrons which are aligned parallel will reorient itself to the field direction and will be easily magnetized. Thus they are named as very strong magnets.
3	When the material is placed in the magnetic field, the magnetic flux lines are repelled away from the material.	When the material is placed in the magnetic field, the magnetic flux lines pass through the material.	When the material is placed in the magnetic field, the magnetic flux lines are highly attracted towards the center of the material.
4	The susceptibility is negative. ($\chi = -ve$)	The susceptibility is positive and small. ($\chi = +ve$)	The susceptibility is positive and large. ($\chi = +ve$)
5	The susceptibility is independent of temperature.	The susceptibility varies inversely with the absolute temperature.	The susceptibility depends upon the temperature.
6	Permeability is less than 1.	Permeability is greater than 1.	Permeability is very much greater than 1.
7	When the temperature is less than critical temperature, the diamagnetism suddenly disappears and becomes a normal material.	When the temperature is less than curie temperature, the paramagnetic material is converted into diamagnetic material.	When the temperature is greater than curie temperature, the ferromagnetic material is converted into paramagnetic material.
8	Examples: gold, bismuth, water, antimony, hydrogen, alcohol, germanium, silicon, etc.	Examples: platinum, chromium, aluminium, copper sulphate, manganese sulphate, etc.	Examples: iron, nickel, cobalt, steel, etc.

ORIGIN OF FERROMAGNETISM AND EXCHANGE INTERACTION

Concept: *Metals contain large number of electrons (i.e.,) free electrons. Each electron possesses a magnetic moment. When the magnetic field is applied, then the elementary electrons behave as magnetic dipoles, which tend to orient along the direction of external magnetic field. Thus the electrons affect the paramagnetism volume susceptibility (χ_c).*

UNIT-2 Electrical and Magnetic Properties of materials

Explanation

Langevin showed that paramagnetic susceptibility varies as $\frac{1}{T}$

$$\chi_c = \frac{1}{T}$$

Where χ_c is called paramagnetic susceptibility.

Its value is 10^{-4} at room temperature but experimental observation shows that the paramagnetic susceptibility value has very small value sy, in the order of 10^{-6} and is independent of temperature. Pauli applied Fermi Dirac statistics to explain this disagreement as follows. Each electron has a magnetic moment $I \mu_B$ along the direction of magnetic field.

If there are 'n' number of conduction electrons per unit volume, then

The net magnetization is

$$M = \mu_B n$$
$$M = \mu_B (n_+ - n_-) \quad \text{----- (1)}$$

Where $n = n_+ - n_-$

Here n_+ is the number of electrons with magnetic moment parallel to the magnetic field B and n_- is the number of electrons with magnetic moment anti-parallel to the magnetic field B.

The concentration of electrons with magnetic moments parallel to the magnetic field is

$$n_+ = \frac{1}{2} \int_{\mu_B}^{E_F} F(E) g(E + \mu_B B) dE \quad \text{----- (2)}$$

$$n_+ = \frac{1}{2} \int_0^{E_F} F(E) g(E) dE + \frac{1}{2} \mu_B B g(E_F) \quad \text{----- (3)}$$

Similarly,

$$n_- = \frac{1}{2} \int_{\mu_B}^{E_F} F(E) g(E - \mu_B B) dE$$

$$n_- = \frac{1}{2} \int_0^{E_F} F(E) g(E) dE - \frac{1}{2} \mu_B B g(E_F) \quad \text{----- (4)}$$

Where F(E) is called Fermi-Dirac distribution function and $\frac{1}{2} g(E \pm \mu_B B)$ is the density of orbitals of one spin (either + or (or) -) orientation.

Substituting equation (3) and equation (4) in equation (1), we get

$$\text{The net magnetization } M = \mu_B \left\{ \frac{1}{2} \int_0^{E_F} F(E) g(E) dE + \frac{1}{2} \mu_B B g(E_F) - \right.$$

$$\left. \left[\frac{1}{2} \int_0^{E_F} F(E) g(E) dE - \frac{1}{2} \mu_B B g(E_F) \right] \right\}$$

$$M = \mu_B [\mu_B B g(E_F)]$$

$$M = \mu_B^2 B g(E_F) \quad \text{----- (5)}$$

We know, density of states

$$g(E_F) = \frac{3}{2} \frac{n}{E_F} \quad \text{----- (6)}$$

UNIT-2 Electrical and Magnetic Properties of materials

Where E_F is the Fermi Energy.

Substituting equation (6) in equation (5), we get

$$M = \mu_B^2 B \frac{3}{2} \frac{n}{E_F} \text{----- (7)}$$

Since $B = \mu_0 H$, we can write equation (7) as

$$M = \mu_B^2 \mu_0 H \frac{3}{2} \frac{n}{E_F}$$
$$\frac{M}{H} = \frac{3}{2} \frac{\mu_B^2 \mu_0 n}{E_F} \text{----- (8)}$$

Since $\chi_c = \frac{M}{H}$, we can write equation (8) as

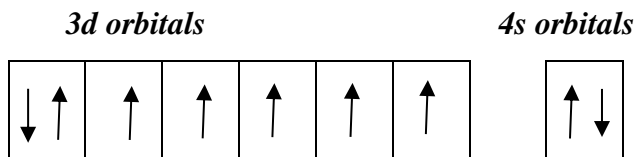
$$\chi_c = \frac{3}{2} \frac{\mu_B^2 \mu_0 n}{E_F} \text{----- (9)}$$

Equation (9) is called as the Pauli's paramagnetic susceptibility of a Fermi gas of conduction electrons.

Here in equation (9) we can note that the susceptibility is independent of temperature thus verifying the experimental also.

ORIGIN OF FERROMAGNETISM AND EXCHANGE INTERACTION

The ferromagnetic property is exhibited by transition elements such as iron, cobalt and nickel at room temperature and rare earth elements such as gadolinium and dysprosium. The ferromagnetic materials possess parallel alignment of dipoles. This parallel alignment of dipoles is not due to the magnetic force existing between any two dipoles. The reason is that the magnetic potential energy is very small and it is smaller than thermal energy.



The electronic configuration of iron is $1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^6$ and $4s^2$. For iron, the six electrons present in the 3d sub shell occupy the orbitals such that there are four unpaired electrons and two paired electrons. These four unpaired electrons contribute a magnetic moment of 4β . This arrangement shows the parallel alignment of four unpaired electrons. The parallel alignment of dipoles in iron is not due to the magnetic interaction. It is due to the Pauli's exclusion principle and electrostatic interaction energy.

UNIT-2 Electrical and Magnetic Properties of materials

The Pauli's exclusion principle and electrostatic interaction energy are combined together and constitute a new kind of interaction known as exchange interaction. The exchange interaction is a quantum mechanical concept.

Quantum Interference Devices

A Quantum Interference Device is a very sensitive device which is used to measure very weak magnetic fields at the order of 5×10^{-18} Tesla, using the principle of interference.

Examples

1. Superconducting quantum interference devices
2. GMR devices etc.

Applications

1. These devices are used in research and biological studies.
2. They are used in ultra-sensitive electronic and magnetic measurements.

Superconducting Quantum Interference Devices (SQUID)

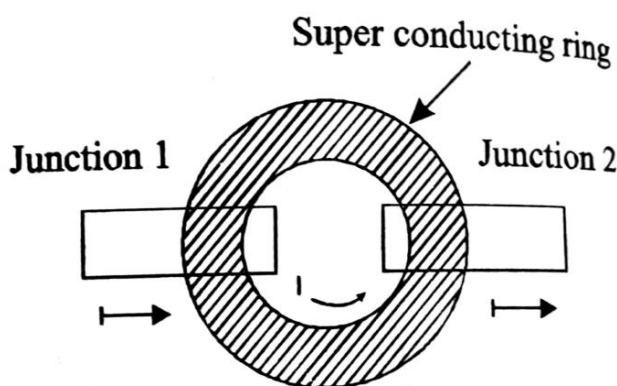
SQUID [Superconducting Quantum Interference Devices] are the improved model of Josephson devices. It has high efficiency, sensitivity and quick performance.

Principle: Small change in magnetic field, produces variation in flux quantum.

Explanation:

It consists of a super conducting rings which can have magnetic fields of quantum values (1,2,3,) of flux placed in between the two Josephson junctions.

When the magnetic field is applied perpendicular to the plane of the ring, current is induced at the two Josephson junctions and produces interference pattern. The induced current flows around the ring so that the magnetic flux in the ring can have quantum values of flux, which corresponds to the value of magnetic field applied. Therefore SQUIDS are used to detect the variation in very minute magnetic signals in terms of quantum flux. They are used as storage devices for magnetic flux. They are also used in the study of earthquakes, removing paramagnetic impurities, detection of magnetic signals from the brain, heart etc.



UNIT-2 Electrical and Magnetic Properties of materials

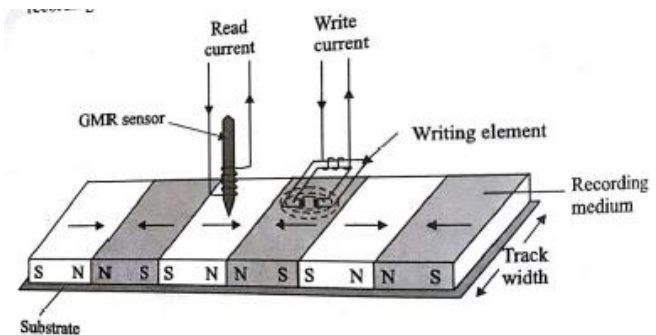
GMR Devices

Giant magnetoresistance (GMR) is a quantum mechanical magnetoresistance effect observed in thin film structures composed of alternating ferromagnetic and nonmagnetic layers. Giant magnetoresistance is a large change in electrical resistance due to spin alignment of electrons in alternating magnetic layers separated by a non-magnetic layer. GMR Devices are widely used as magnetic sensors, read heads in hard disks, magnetometers, compass system, etc.

MAGNETIC HARD DISK DRIVE (HDD) WITH GMR SENSOR

The GMR read head sensor in a hard disk is built using a spin valve. Spin valve resistance demonstrates a steep change in the small field range close to $H=0$. As the magnetic bits on the hard drive pass under the read head, the magnetic alignment of the sensing layer in the spin valve changes resulting in the resistance change.

As the read head passes over the disk, the free layer shifts its magnetic orientation to match that of the bit. So sometimes the direction of the free layer's magnetic field is aligned with the field of the pinned layer (which never changes), and sometimes it is opposite. When they are aligned, most of their electrons will share the same up or down spin. As some of these electrons pass through the layers in the form of current, there will be minimal scattering. The low resistance means a current will be detected, and the computer computes a 1 bit.



When the free layer's magnetic orientation switches to opposite that of the pinned layer, there's a much different result. The electrons in the two layers have opposing spins. So as the current passes through the magnetized layers, those electrons will scatter in one or the other of them, resulting in a much weaker current and a 0 bit.

PROBLEMS

1. Calculate the drift velocity of the free electron with a mobility of $3.5 \times 10^{-3} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ in copper for an electric field strength of 0.5 V/m.

$$\text{Drift Velocity } v_d = \mu E$$

$$v_d = 3.5 \times 10^{-3} \times 0.5$$

$$v_d = 1.75 \times 10^{-3} \text{ m/s}$$

$$v_d = 0.00175 \text{ m/s}$$

UNIT-2 Electrical and Magnetic Properties of materials

2. A conducting rod contains 8.5×10^{28} electrons per m^3 . Calculate the electrical conductivity at room temperature if the collision time for electron is $2 \times 10^{-14} \text{s}$.

$$\sigma = \frac{ne^2\tau}{m}$$
$$\sigma = \frac{(8.5 \times 10^{28} \times (1.609 \times 10^{-19})^2 \times 2 \times 10^{-14})}{9.11 \times 10^{-31}}$$
$$\sigma = 4.83 \times 10^7 \text{ mho/m}$$

3. The mobility of electron in copper is $3 \times 10^{-3} \text{ m}^2/\text{Vs}$. Assuming $e = 1.6 \times 10^{-19} \text{ C}$ and $m_e = 9.1 \times 10^{-31} \text{ kg}$, calculate the mean free time.

$$\sigma = \frac{ne^2\tau}{m} \quad \text{and} \quad \sigma = \mu n e$$

Equating above eqns we can write $\tau = \frac{\mu m}{e}$

$$\text{Mean free time } \tau = \frac{3 \times 10^{-3} \times 9.1 \times 10^{-31}}{1.6 \times 10^{-19}}$$
$$\text{Mean free time } \tau = 1.70625 \times 10^{-14} \text{ seconds}$$

4. Evaluate the Fermi function for energy $K_B T$ above the Fermi energy.

$$E - E_F = K_B T$$
$$F(E) = \frac{1}{1 + e^{(E - E_F)/K_B T}} \quad F(E) = \frac{1}{1 + e^{K_B T/K_B T}} \quad F(E) = \frac{1}{1 + \exp(1)}$$
$$F(E) = \frac{1}{1 + 2.78} \quad F(E) = 0.269$$

5. The Fermi temperature of a metal is 24600 K . Calculate the Fermi velocity.

The relation between Fermi energy, Fermi velocity and Fermi temperature is given by

$$E_F = K_B T_F = \frac{1}{2} m v_F^2$$
$$v_F = \sqrt{\frac{2 K_B T_F}{m}} = \sqrt{\frac{2 \times 1.38 \times 10^{-23} \times 24600}{9.11 \times 10^{-31}}}$$
$$v_F = 0.8633 \times 10^6 \text{ m/s}$$

6. Calculate the electrical and thermal conductivities for a metal with a relaxation time 10^{-14} second at 300 K . Also calculate Lorentz number using the above result. (Density of electrons = $6 \times 10^{28} \text{ m}^{-3}$).

UNIT-2 Electrical and Magnetic Properties of materials

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

$$\sigma = \frac{6 \times 10^{28} \times (1.6 \times 10^{-19})^2 \times 10^{-14}}{9.11 \times 10^{-31}}$$

$$\sigma = 1.686 \times 10^7 \text{ mho m}^{-1}.$$

$$\text{Thermal conductivity } K = \frac{\pi^2}{3} \frac{nk^2\tau T}{m}$$

$$K = \frac{3.14^2}{3} \frac{6 \times 10^{28} \times (1.38 \times 10^{-23})^2 \times 10^{-14} \times 300}{9.11 \times 10^{-31}}$$

$$K = 123.80 \text{ W/m/K}$$

$$\text{Lorentz Number } L = \frac{K}{\sigma T}$$

$$L = \frac{123.92}{1.686 \times 10^7 \times 10^{-14}}$$

$$L = 2.45 \times 10^{-8} \text{ W}\Omega\text{K}^{-2}$$

7. The density of silver is $10.5 \times 10^3 \text{ kg/m}^3$. The atomic weight of silver is 107.9. Each silver atom provides one conduction electron. The conductivity of silver at 20°C is $6.8 \times 10^7 \Omega^{-1}\text{m}^{-1}$. Calculate the density of electron and also the mobility of electrons in silver.

$$\text{Number of atoms present per m}^3 = \text{Avagadro No.} \times \frac{\text{Density}}{\text{Atomic weight}}$$

$$= \frac{6.023 \times 10^{23} \times 10.5 \times 10^3}{107.9 \times 10^{-3}}$$

$$\text{Number of atoms present per m}^3 = 5.86 \times 10^{28} \text{ atoms/m}^3$$

$$\mu = \frac{\sigma}{ne}$$

$$\mu = \frac{6.8 \times 10^7}{5.86 \times 10^{28} \times 1.6 \times 10^{-19}} \quad \mu = 0.72 \times 10^{-2} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$$

8. Use the Fermi distribution function to obtain the value of $F(E)$ for the level just 0.01eV above the Fermi level at 200 K .

$$E - E_F = 0.01\text{eV}$$

$$F(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

$$F(E) = \frac{1}{1 + \exp\left(\frac{0.01 \times 1.6 \times 10^{-19}}{1.38 \times 10^{-23} \times 200}\right)}$$

UNIT-2 Electrical and Magnetic Properties of materials

$$F(E) = \frac{1}{1 + e^{0.05797}}$$

$$F(E) = 0.3589$$

9. The Fermi energy of silver is 5.51 eV. What is the average energy of a free electron at 0K?

$$\overline{E_{\text{avg}}} = \frac{3}{5} E_F$$

$$\overline{E_{\text{avg}}} = \frac{3}{5} (5.51 \times 1.6 \times 10^{-19})$$

$$\overline{E_{\text{avg}}} = 5.2896 \times 10^{-19} \text{ J}$$

$$\overline{E_{\text{avg}}} = 3.306 \text{ eV}$$

10. Magnetic field Intensity of a paramagnetic material is 104 A/m. At room temperature, its susceptibility is 3.7×10^{-3} . Calculate the magnetization in the material.

$$\chi = \frac{I}{H}$$

$$I = \chi H$$

$$I = 3.7 \times 10^{-3} \times 10^4$$

$$I = 37 \text{ Am}^{-1}$$

11. A magnetic field of 1800 ampere/meter produces a magnetic flux of 3×10^{-5} weber in an iron bar of cross sectional area 0.2 cm^2 . Calculate permeability.

$$B = \frac{\Phi}{A}$$

$$B = \frac{3 \times 10^{-5}}{0.2 \times 10^{-4}}$$

$$B = 1.5 \text{ Wb/m}^2$$

$$\mu = \frac{B}{H}$$

$$\mu = \frac{1.5}{1800}$$

$$\mu = 8.333 \times 10^{-4} \text{ Hm}^{-1}.$$

12. A magnetic field of 2000 A/m is applied to a material which has a susceptibility of 1000. Calculate the (i) Intensity of Magnetization and (ii) Flux density.

$$\text{Intensity of Magnetization } I = \chi_m H \quad I = 1000 \times 2000$$

Rotate Left 90°.

$$I = 2 \times 10^6 \text{ A/m.}$$

$$\text{Flux Density } B = \mu_0 (I + H)$$

$$B = 4 \times 3.14 \times 10^{-7} \times (2 \times 10^6 + 2000)$$

$$B = 2.514 \text{ Wb/m}^2.$$

UNIT-2 Electrical and Magnetic Properties of materials

13. The magnetic susceptibility of a medium is 940×10^{-4} . Calculate its absolute and relative permeability.

$$\text{Relative permeability } \mu_r = 1 + \chi$$

$$\text{Relative permeability } \mu_r = 1 + (940 \times 10^{-4})$$

$$\text{Relative permeability } \mu_r = 1 + (0.094)$$

$$\text{Relative permeability } \mu_r = 1.094$$

$$\text{Absolute permeability } \mu = \mu_0 \mu_r$$

$$\text{Absolute permeability } \mu = 4\pi \times 10^{-7} \times 1.094$$

$$\text{Absolute permeability } \mu = 13.74 \times 10^{-7} \text{ N/A}^2$$

14. Iron has relative permeability of 5000. Calculate its magnetic susceptibility.

$$\begin{aligned}\chi &= \mu_r - 1 \\ \chi &= 5000 - 1 \\ \chi &= 4999\end{aligned}$$

15. The magnetic field strength of silicon is 1500 A/m. if the magnetic susceptibility is , calculate the magnetization and flux density in Silicon.

$$\text{Intensity of magnetization } I = \chi_m H$$

$$I = -0.3 \times 10^{-5} \times 1500$$

$$I = -4.5 \times 10^{-3} \text{ A/m}$$

$$\text{Flux density } B = \mu H$$

$$B = \mu H$$

$$B = (1 + \chi_m) H$$

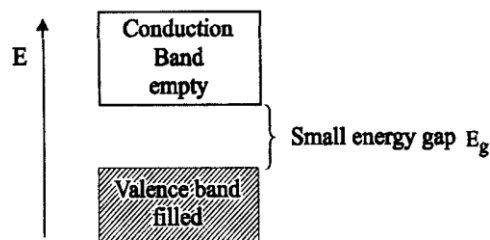
$$B = (1 - 0.3 \times 10^{-5}) 1500$$

$$B = (0.999997) 1500$$

$$B = 1499.9 \text{ Wb/m}^2$$

Intrinsic Semiconductors – Energy band diagram – direct and indirect band gap semiconductors – Carrier concentration in intrinsic semiconductors – extrinsic semiconductors - Carrier concentration in N-type & P-type semiconductors – Variation of carrier concentration with temperature – Carrier transport in Semiconductors: Drift, mobility and diffusion – Hall effect and devices – Ohmic contacts – Schottky diode.

A semiconductor is a solid which has the resistivity in between the conductor and the insulator. It act as insulator at low temperature and act as conductors at high temperature. Examples: Germanium, Silicon, GaAs, InP, etc. The resistivity of semiconductors are from 10^{-4} to 0.5 ohm – metre. The study of semiconducting materials is essential for engineers due to their wide application in semiconductor devices in engineering and technology.



Energy band diagram of a semiconductor

Properties of semiconductors:

- ✓ The resistivity lies between 10^{-4} to 0.5 ohm meters.
- ✓ At 0K, they behave as insulators.
- ✓ They empty conduction band and almost filled valence band.
- ✓ The conductivity of a semiconductor increases both due to the temperature and impurities.
- ✓ They have negative temperature coefficient of resistance.
- ✓ In semiconductors both the electron and holes are charge carriers and will take part in conduction.

Classification of semiconductors:

Based on composition they are classified as

- (i) Elemental semiconductors (ii) Compound semiconductors

UNIT III – SEMICONDUCTORS AND TRANSPORT PHYSICS

(i) Elemental semiconductors: They are made from a single element of fourth group elements of the periodic table. They are also called as indirect band gap semiconductors.

Examples: Germanium, Silicon, Diamond.

(ii) Compound semiconductors: They are formed by combining third and fifth group elements or second and sixth group elements in the periodic table. They are also called as direct band gap semiconductors. **Examples:** GaP, GaAs, MgO, ZnO, ZnS.

S.No	Elemental semiconductors	Compound semiconductors
1	They are made up of single element.	They are made up of compounds.
2	They are made from a single element of fourth group elements of the periodic table.	They are formed by combining third and fifth group elements or second and sixth group elements in the periodic table.
3	They are called indirect band gap semiconductors.	They are called as direct band gap semiconductors.
4	Here heat is produced during recombination.	Here the photons are emitted during recombination.
5	Life time of charge carriers is more.	Life time of charge carriers is less.
6	Current amplification is more.	Current amplification is less.
7	They are used in the manufacture of diodes and transistors, etc.	They are used for making LED's, laser diodes, IC's, etc.
8	Examples: Ge, Si, etc.	Examples: GaAs, GaP, CdS, MgO, etc.

Types of semiconductors:

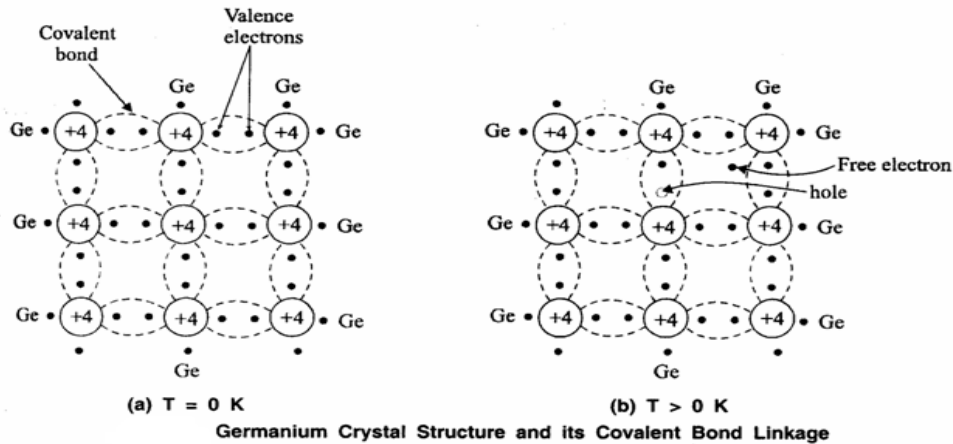
Depending on the impurity added, there are two types.

- (i) Intrinsic semiconductor (or) pure semiconductors
- (ii) Extrinsic semiconductor (or) impure semiconductors
 - (a) N-type semiconductor
 - (b) P-type semiconductor

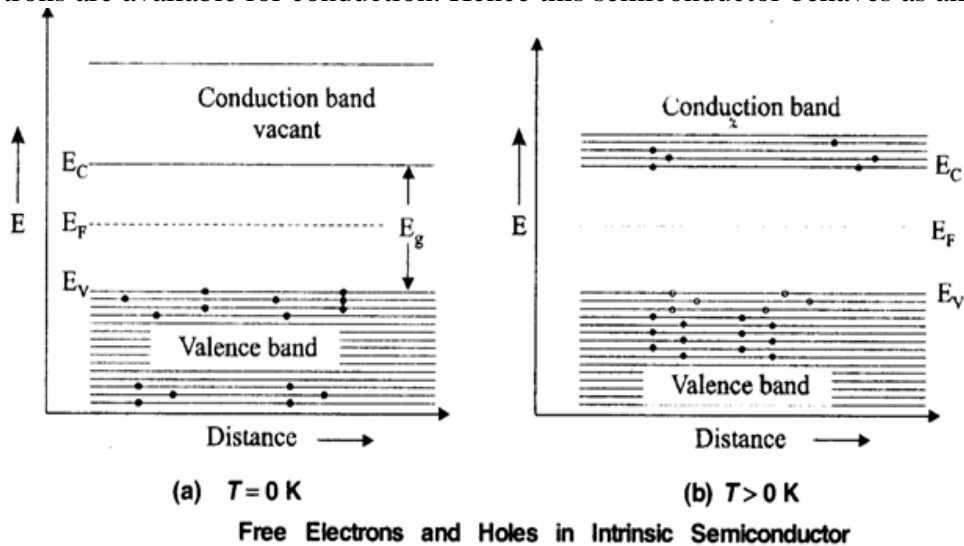
Intrinsic semiconductor:

The semiconductor in extremely pure form, without addition of impurities is known as an intrinsic semiconductor. In intrinsic semiconductor, holes and electrons are created by thermal agitation. As there are no impurities the number of free electrons must be equal to the number of holes. **Examples:** silicon and germanium.

UNIT III – SEMICONDUCTORS AND TRANSPORT PHYSICS



They belong to the fourth group element in the periodic table. They are tetravalent atoms since they have four valence electrons. The neighboring atoms form covalent bonds by sharing four electrons with each other so as to form a stable structure. At very low temperatures say 0 K , no free electrons are available for conduction. Hence this semiconductor behaves as an insulator.



Carrier concentration in intrinsic semiconductors:

The number of electrons in the conduction band per unit volume of the material or the number of holes in the valence band of the material is known as carrier concentration. It is also known as density of charge carriers.

Calculation of density of electrons in conduction band:

The number of electrons in the energy interval E and $E + dE$ is given by

UNIT III – SEMICONDUCTORS AND TRANSPORT PHYSICS

$$dn = Z(E) F(E) dE \quad \dots\dots\dots(1)$$

Where $Z(E) dE \rightarrow$ Density of energy states

$F(E) \rightarrow$ Electron probability occupancy.

The number of electrons in the conduction band for the entire region is calculated by integrating the equation (1) from energy E_c to $+\infty$.

$$\therefore n = \int dn = \int_{E_c}^{+\infty} Z(E)F(E)dE \dots\dots\dots (2)$$

Where

$$Z(E) dE = \frac{4\pi}{h^3} (2m_e^*)^{3/2} E^{1/2} dE \dots\dots\dots(3)$$

The electrons in the conduction band are move in a periodic potential , so $m = m_e^*$

Where $m_e^* \rightarrow$ Effective mass.

$E_c \rightarrow$ The potential energy of an electron at rest.

$E - E_c \rightarrow$ The kinetic energy of the conduction electron at higher energy levels.

\therefore Equation (3) is modified as

$$Z(E)dE = \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_c)^{1/2} dE \quad \dots\dots\dots(4)$$

$$\text{Where } F(E) = \frac{1}{1 + e^{(E - E_F)/kT}} \quad \dots\dots\dots(5)$$

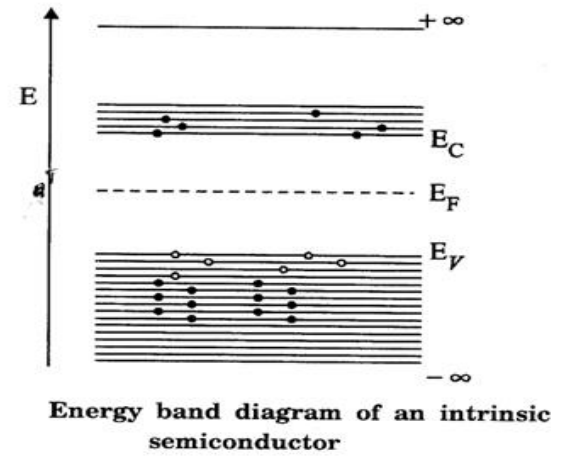
Substitute equation (4) and (5) in equation (2) we have

$$n = \int_{E_c}^{+\infty} \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_c)^{1/2} \frac{1}{1 + e^{(E - E_F)/kT}} dE$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_c}^{+\infty} (E - E_c)^{1/2} \frac{1}{1 + e^{(E - E_F)/kT}} dE \quad \dots\dots\dots (6)$$

Since kT is very small and $e^{(E - E_F)/kT}$ is very large compared to 1. \therefore 1 from the denominator of equation (6) is neglected.

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_c}^{+\infty} (E - E_c)^{1/2} e^{-(E - E_F)/kT} dE$$



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$$n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_c}^{+\infty} (E - E_c)^{\frac{1}{2}} e^{(E_F - E)/kT} dE$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{E_F/kT} \int_{E_c}^{+\infty} (E - E_c)^{\frac{1}{2}} e^{-\frac{E}{kT}} dE \quad \dots\dots\dots(7)$$

Take $E - E_c = x$, $dE = dx$, $E = E_c + x$

When $E = E_c$, $E_c - E_c = x$, $x=0$

When $E = +\infty$, $+\infty - E_c = x$, $x = +\infty$

Substituting the above values in equation (7) we have

$$n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{E_F/kT} \int_0^{+\infty} x^{\frac{1}{2}} e^{-(E_c + x)/kT} dx$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{(E_F - E_c)/kT} \int_0^{+\infty} x^{\frac{1}{2}} e^{-x/kT} dx \quad \dots\dots\dots(8)$$

Using the gamma function, $\int_0^{+\infty} x^{\frac{1}{2}} e^{-\left(\frac{x}{kT}\right)} dx = \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2} \quad \dots\dots\dots(9)$

Substituting equation (9) in equation (8) we have $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{(E_F - E_c)/kT} \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_c)/kT} \quad \dots\dots\dots(10)$$

This is the expression for the concentration of electrons in the conduction band of an intrinsic semiconductor.

Calculation of density holes in the valence band:

If an electron is transferred from valence band to conduction band, a hole is created in the valence band. Let dP be the number of holes in the valence band for the energy range E and

$$E+dE \quad dP = Z(E) (1-F(E))dE \quad \dots\dots\dots(1)$$

Where $1-F(E) \rightarrow$ Probability of an unoccupied electron state i.e., presence of a hole

$$1-F(E) = 1 - \left[\frac{1}{1 + e^{\frac{(E-E_F)}{kT}}} \right] \quad 1-F(E) = \frac{1 + e^{\frac{(E-E_F)}{kT}} - 1}{1 + e^{\frac{(E-E_F)}{kT}}} \quad 1-F(E) = \frac{e^{\frac{(E-E_F)}{kT}}}{1 + e^{\frac{(E-E_F)}{kT}}} \quad \dots\dots\dots(2)$$

E is very small compared to E_F , $e^{\frac{(E-E_F)}{kT}}$ is very small. So the second term in the denominator of equation (2) is neglected. ie, $1 + e^{\frac{(E-E_F)}{kT}} \approx 1$

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$$\therefore 1-F(E) = e^{\frac{(E-E_F)}{kT}} \dots\dots\dots(3)$$

$$\text{Density of states in the valence band } Z(E) dE = \frac{4\pi}{h^3} (2m_h^*)^{3/2} E^{1/2} dE \dots\dots\dots(4)$$

Where $m_h^* \rightarrow$ Effective mass of the hole in the valence band.

$E_v \rightarrow$ the potential energy of a hole at rest.

$E_v - E \rightarrow$ the kinetic energy of the hole at level below E_v .

$$\therefore \text{Equation (4) is modified as } Z(E)dE = \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_v - E)^{1/2} dE \dots\dots\dots(5)$$

Substitute equation (3) and (5) in equation (1) we have

$$dP = \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_v - E)^{1/2} e^{\frac{(E-E_F)}{kT}} dE \dots\dots\dots(6)$$

Integrating equation (6) with respect to limit $-\infty$ to E_v

$$\begin{aligned} \int dP &= \int_{-\infty}^{E_v} \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_v - E)^{1/2} e^{\frac{(E-E_F)}{kT}} dE \\ P &= \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{-E_F/kT} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{\frac{E}{kT}} dE \end{aligned} \dots\dots\dots(7)$$

Take $E_v - E = x$, $dE = -dx$, $E = -x + E_v$

When $E = E_v$, $x = E_v - E_v$, $x = 0$

When $E = -\infty$, $x = E_v + \infty$, $x = +\infty$

Substituting the above values in equation (7) we have

$$P = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{-E_F/kT} \int_{\infty}^0 (x)^{1/2} e^{\frac{(-x+E_v)}{kT}} (-dx) \dots\dots\dots(8)$$

$$P = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(E_v-E_F)/kT} \int_0^{\infty} (x)^{1/2} e^{\frac{(-x)}{kT}} (dx) \dots\dots\dots(9)$$

$$\text{Using the gamma function, } \int_0^{\infty} (x)^{1/2} e^{-\frac{x}{kT}} dx = \frac{(kT)^{3/2} \pi^{1/2}}{2} \dots\dots\dots(10)$$

$$\text{Substituting equation (10) in equation (9) we have } P = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(E_v-E_F)/kT} \frac{(kT)^{3/2} \pi^{1/2}}{2}$$

$$P = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v-E_F)/kT} \dots\dots\dots(11)$$

This is the expression for the concentration of holes in the valence band of an intrinsic semiconductor.

Intrinsic carrier concentration:

In an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of the holes in the valence band. We can rewrite $n = p = n_i$

Where $n_i \rightarrow$ Intrinsic carrier concentration

$$\begin{aligned}np &= n_i \times n_i \quad \text{and} \quad np = n_i^2 \\ \therefore n_i^2 &= 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_c)/kT} \times 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F)/kT} \\ n_i^2 &= 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} e^{(E_v - E_c)/kT} \\ n_i^2 &= 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} e^{(-E_g)/kT}\end{aligned}$$

where $E_c - E_v = E_g$, $E_g \rightarrow$ Forbidden energy gap

$$\therefore n_i = 2 \left(\frac{2\pi kT}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} e^{(-E_g)/2kT} \quad \dots\dots\dots(12)$$

Limitations of intrinsic semiconductor

Intrinsic semiconductors cannot be directly used to fabricate devices due to the following limitations;

- (i) Electrical conductivity is low. Germanium has a conductivity of $1.67 \, \Omega^{-1} m^{-1}$ which is nearly 10^7 times smaller than that of copper.
- (ii) Electrical conductivity is a function of temperature and increases exponentially as the temperature increases.

In intrinsic or pure semiconductors, the carrier concentration of both electrons and holes is very low at normal temperatures. In order to get sufficient current density through semiconductor, a large electrical field should be applied. This problem is overcome by adding suitable impurities into intrinsic semiconductors.

Extrinsic semiconductor:

Impure semiconductors in which charge carriers are produced due to the impurity atoms are called extrinsic semiconductors. It is also known as doped semiconductor. The addition of impurities to a pure semiconductor is known as doping and added impurity is called as doping agent or dopant. The addition of impurities increases the number of free electrons and holes in semiconductor and hence increases its electrical conductivity. Some of the common doping agents are arsenic, aluminium and boron.

Depending on the impurity atom they are classified into two types

- (i) n- type semiconductor and (ii) p- type semiconductor

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n- type semiconductor: They are obtained by doping an intrinsic semiconductor with pentavalent impurity atoms like phosphorous and arsenic. The four valence electron of impurity atom will be bonded with four valence electrons of semiconducting atom and one electron is free which is responsible for conduction. Majority carriers are electrons.

p- type semiconductor: They are formed by doping an intrinsic semiconductor with trivalent impurity atoms like Gallium and Indium. The three valence electrons of the impurity atom pairs with three valence electrons of the semiconductor and one position of the impurity atom is left free (vacant). The excess holes produced are the majority carriers.

S.no	Intrinsic Semiconductor	Extrinsic semiconductor
1	Semiconductor in a pure form is called intrinsic semiconductor. Example: Si, Ge	Semiconductor which are doped with impurity is called Extrinsic semiconductor Example: Si, Ge doped with Al, In,P
2	The charge carriers are produced only due to thermal agitation.	The charge carriers are produced due to impurities and may also be produced due to thermal agitation.
3	They have low electrical conductivity	They have high electrical conductivity.
4	They have low operating temperature.	They have high operating temperature.
5	At 0 K, Fermi level exactly lies between conduction band and valence band.	At 0 K, Fermi level lies closer to conduction band in n-type semiconductor and lies near valence band in p-type semiconductor.

S.no	n- type Semiconductor	p-type semiconductor
1	n-type semiconductor is obtained by doping an intrinsic semiconductor with pentavalent impurity.	p-type semiconductor is obtained by doping an intrinsic semiconductor with trivalent impurity.
2	Here electrons are majority carriers and holes are minority carriers.	Here holes are majority carriers and electrons are minority carriers.
3	It has donor energy level very close to conduction band.	It has acceptor energy level very close to valence band.
4	When the temperature is increased, these semiconductors can easily donate an electron from the donor energy level to the conduction band.	When the temperature is increased, these semiconductors can easily accept an electron from the valence band to acceptor energy level.

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5	Fermi level lies exactly at the middle of the donor level and the bottom of the conduction band $E_F = \frac{(E_d + E_c)}{2}$	Fermi level lies exactly at the middle of the acceptor level and the top of the valence band $E_F = \frac{(E_a + E_v)}{2}$
6	Fermi level decreases with increase of temperature.	Fermi level increases with increase of temperature.

n- type semiconductor:

When a small amount of pentavalent impurity is added to a pure semiconductor. Such impurities are known as donor impurities because they donate free electrons to the semiconductor crystal. In n- type semiconductor electrons are majority charge carriers and holes are minority charge carriers.

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. 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.

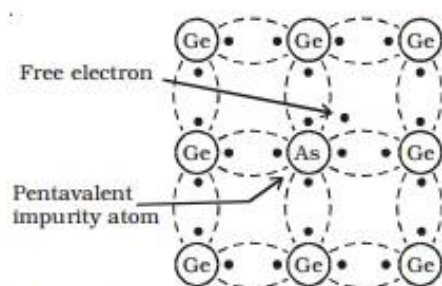


Fig a N-type semiconductor

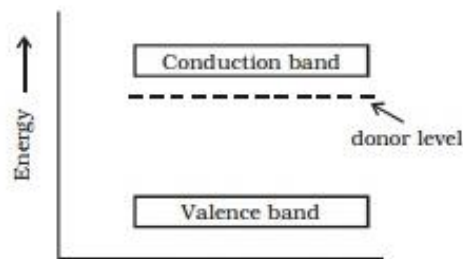


Fig b Energy band diagram of N-type semiconductor

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Carrier concentration in n- type semiconductor:

In an n-type semiconductor, the donor level is just below the conduction band. N_d denotes the donor concentration and E_d denotes the energy of donor level.

Density of electrons per unit volume in the conduction band is given by

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_C)/kT} \quad \dots\dots\dots(1)$$

Density of ionized donors = $N_d(1 - F(E_d))$

$$\begin{aligned} &= N_d \left(1 - \left[\frac{1}{1 + e^{\frac{(E_d - E_F)}{kT}}} \right] \right) \\ &= N_d \left[\frac{1 + e^{\frac{(E_d - E_F)}{kT}} - 1}{1 + e^{\frac{(E_d - E_F)}{kT}}} \right] \\ &= N_d \left[\frac{e^{\frac{(E_d - E_F)}{kT}}}{1 + e^{\frac{(E_d - E_F)}{kT}}} \right] \end{aligned}$$

If E_F lies more than a few kT above donor levels. So the denominator may be neglected.

$$\therefore \text{Density of ionized donors} = N_d \left[e^{\frac{(E_d - E_F)}{kT}} \right] \quad \dots\dots\dots(2)$$

At equilibrium density of electrons in the conduction band is equal to the density of ionized donors.

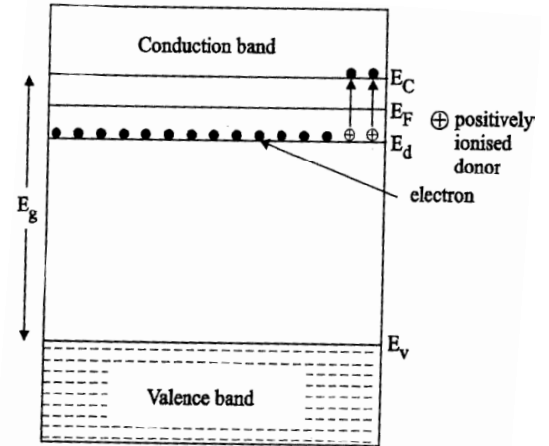
$$2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_C)/kT} = N_d \left[e^{\frac{(E_d - E_F)}{kT}} \right] \quad \dots\dots\dots(3)$$

Taking log on both sides, we get

$$\log \left[2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_C)/kT} \right] = \log \left(N_d \left[e^{\frac{(E_d - E_F)}{kT}} \right] \right)$$

Rearranging,

$$\begin{aligned} \frac{E_F - E_C - E_d + E_F}{kT} &= \log \left[\frac{N_d}{2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2}} \right] \\ \frac{2E_F - (E_d + E_C)}{kT} &= \log \left[\frac{N_d}{2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2}} \right] \end{aligned}$$



Energy band diagram of a n-type semiconductor

$$2E_F = (E_d + E_c) + kT \log \left[\frac{N_d}{2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}}} \right]$$

$$E_F = \frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}}} \right] \quad \dots\dots\dots(4)$$

Substituting the expression of E_F from equation (5) in (1)

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp \left[\frac{\frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}}} \right] - E_c}{kT} \right]$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp \left[\frac{kT}{2kT} \log \left[\frac{N_d}{2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}}} \right] + \frac{E_d + E_c - 2E_c}{2kT} \right]$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp \left[\frac{1}{2} \log \left[\frac{N_d}{2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}}} \right] + \frac{E_d - E_c}{2kT} \right]$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp \left[\log \frac{(N_d)^{\frac{1}{2}}}{(2)^{\frac{1}{2}} \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{4}}} + \frac{(E_d - E_c)}{2kT} \right]$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \frac{(N_d)^{\frac{1}{2}}}{(2)^{\frac{1}{2}} \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{4}}} \exp \left[\frac{E_d - E_c}{2kT} \right]$$

$$n = (2N_d)^{\frac{1}{2}} \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{4}} \exp \left[\frac{-\Delta E}{2kT} \right] \quad \text{where } \Delta E = E_c - E_d$$

$\Delta E \rightarrow$ Ionisation energy of the donor. ie, The amount of energy required to transfer an electron from donor energy level E_d to conduction band E_c .

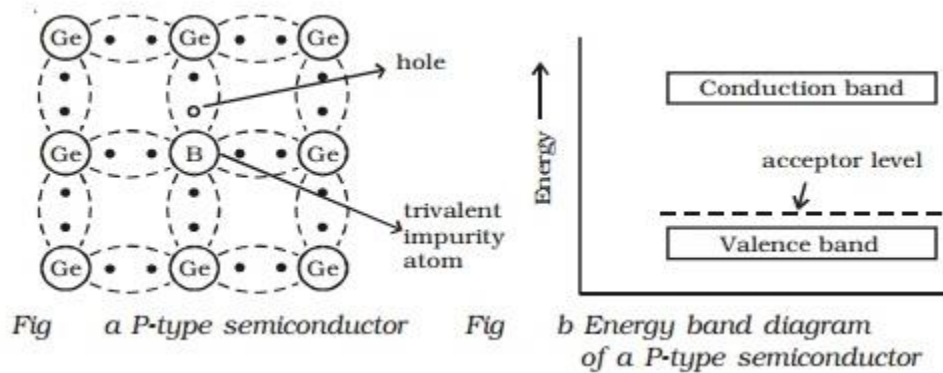
$$n = (2N_d)^{\frac{1}{2}} \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{4}} \exp \left[\frac{-\Delta E}{2kT} \right]$$

It is clear that the density of electrons in the conduction band is directly proportional to the square root of donor concentration.

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p- type semiconductor:

When a small amount of trivalent impurity is added to a pure semiconductor, it becomes p- type semiconductor typical examples of trivalent impurities are gallium and indium. Such impurities are known as acceptor impurities because the holes they create can accept electrons. In p- type semiconductor holes are majority charge carriers and electrons are minority charge carriers.



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. 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.

Carrier concentration in p- type semiconductor:

In p-type semiconductors, the acceptor level is just above the valence band. Let E_a represent the energy of the acceptor level, and N_a represent the number of acceptor atoms per unit volume.

Density of holes per unit volume in the valence band is given by

$$P = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F)/kT} \quad \dots\dots\dots(1)$$

$$\text{Density of ionized acceptors} = N_a F(E_a) = N_a \left[\frac{1}{1 + e^{\frac{(E_a - E_F)}{kT}}} \right]$$

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Since $E_a - E_F \gg kT$, $e^{\frac{(E_a - E_F)}{kT}}$ is very large quantity and thus 1 can be neglected from the denominator.

$$\therefore \text{Density of ionized acceptors} = N_a \left[e^{\frac{(E_F - E_a)}{kT}} \right] \quad \dots\dots\dots(2)$$

At equilibrium density of holes in the valence band is equal to the density of ionized acceptors.

$$2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F)/kT} = N_a \left[e^{\frac{(E_F - E_a)}{kT}} \right]$$

Taking log on both sides, we get

$$\log \left(2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F)/kT} \right) = \log \left(N_a \left[e^{\frac{(E_F - E_a)}{kT}} \right] \right)$$

Rearranging,

$$\frac{E_v - E_F - E_F + E_a}{kT} = \log \left[\frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right]$$

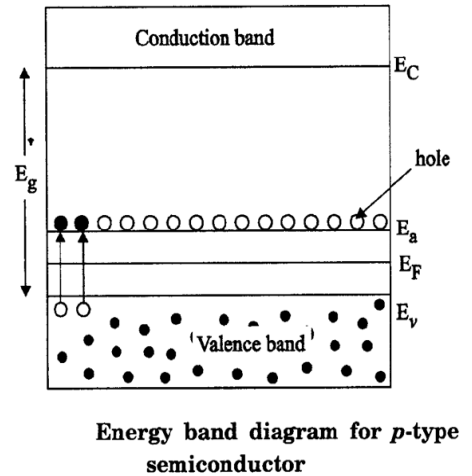
$$\frac{-2E_F + (E_a + E_v)}{kT} = \log \left[\frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right]$$

$$-2E_F = -(E_a + E_v) + kT \log \left[\frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right]$$

$$E_F = \frac{(E_a + E_v)}{2} - \frac{kT}{2} \log \left[\frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right] \quad \dots\dots\dots(3)$$

Substituting the expression of E_F from equation (3) in (1)

$$p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp \left[\frac{E_v - \frac{(E_a + E_v)}{2} - \frac{kT}{2} \log \left[\frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right]}{kT} \right]$$



$$p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp \left[\frac{kT}{2kT} \log \left[\frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right] + \frac{2E_v - E_a - E_v}{2kT} \right]$$

$$p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp \left[\frac{1}{2} \log \left[\frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right] + \frac{E_v - E_a}{2kT} \right]$$

$$p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp \left[\log \frac{(N_a)^{1/2}}{(2)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4}} + \frac{E_v - E_a}{2kT} \right]$$

$$p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \frac{(N_a)^{1/2}}{(2)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4}} \exp \left[\frac{(E_v - E_a)}{2kT} \right]$$

$$p = (2N_a)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4} \exp \left[\frac{-\Delta E}{2kT} \right] \quad \text{where } \Delta E = E_a - E_v$$

$\Delta E \rightarrow$ Ionisation energy of the acceptor.

ie, The amount of energy required to transfer an holes from acceptor energy level E_a to valence band E_v .

$$p = (2N_a)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4} \exp \left[\frac{-\Delta E}{2kT} \right]$$

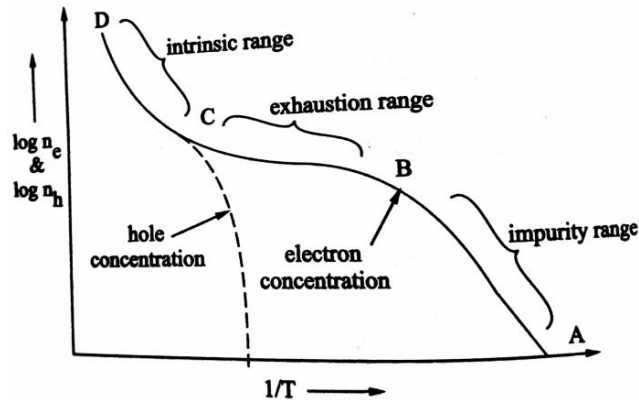
It is clear that the density of holes in the valence band is directly proportional to the square root of acceptor concentration.

Variation of carrier concentration with temperature

In extrinsic semiconductors, the resistivity decreases linearly with increase in temperature. This variation is considered under three different regions.

- (i) Extrinsic or impurity range
- (ii) Exhaustion range
- (iii) Intrinsic range

For an n-type semiconductor, the variation of carrier concentration n and p with temperature is shown in the graph. At 0 K, both conduction and valence bands are free from any charge carriers and hence the electrical conductivity is zero.



Now when the temperature is slowly increased, the donor atom gets ionized and the electrons move towards the conduction band. Here the carrier concentration (n_e) increases slowly in the conduction band for electrons. Since this range is obtained due to impurity atoms, it is called **impurity range** shown by the curve AB.

When the temperature is further increased to reach up to say room temperature, all donor atoms are ionized and hence the carrier concentration increases in the conduction band and reaches to a steady state. Since this range is obtained due to exhaustion of donor atoms, it is called **exhaustion range** shown by the curve BC.

When the temperature is still further increased, due to thermal ionization, the electron from the valence band is lifted up to go to the conduction band and hence there is an increase in the carrier concentration (n_e). In this case the number of electrons in the donor energy level is almost exhausted, many number of electrons are shifted from valence band to conduction band and hence the carrier concentration increases rapidly, tracing the curve CD. Since the material practically becomes intrinsic in this range, this range is known as **intrinsic range**.

The dotted curve indicates the hole concentration in an intrinsic range.

Carrier transport in semiconductor

Random motion and mobility

In absence of an electrical field the free electrons move in all directions in a random manner. They collide with other free electrons and positive ion core during the motion. This collision is known as elastic collision.

As the motion is random the resultant velocity in any particular direction is zero. When an electrical field is applied in a semiconducting material the free charge carriers such as free

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electrons and holes attain drift velocity V_d . The drift velocity attained by the carriers is proportional to the electric field *strength* E .

$$V_d \propto E \qquad V_d = \mu E$$

Where μ is a proportionality constant and it is known as the mobility of the charge carrier. This velocity V_d is different for different semiconductors and for different type of charge carriers.

$$\text{If } E = 1 \text{ V/m then } \mu = V_d.$$

Thus **mobility μ is defined as the velocity of charge carrier per unit electrical field strength.** μ_n and μ_p denote electron mobility and hole mobility respectively. Since the types of drift of electrons and of holes are different the mobility of an electron at any temperature is different from that of hole.

The electrical conductivity σ_i of an intrinsic semiconductor having n_i electron – hole pairs per unit volume is given by

$$\sigma_i = e n_i (\mu_n + \mu_p)$$

Drift and diffusion Transport

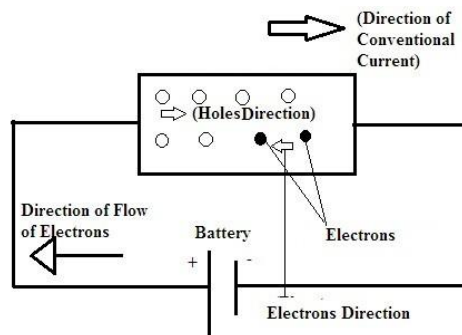
The net current flow across a semiconductor has two components:

- (i) Drift current (ii) Diffusion current.

Drift current

Definition: The electric current produced due to the motion of charge carriers under the influence of an external electric field is known as drift current.

When electrical voltage is applied to a material, electric field is produced at every point within the material. The charge carriers are forced to move in a particular direction due to the electric field. This is known as the drift motion and the current is known as drift current.



Drift current in a semiconductor due to electrons $J_n(\text{drift}) = n\mu_n eE$

Drift current in a semiconductor due to holes $J_p(\text{drift}) = p\mu_p eE$

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Where n and p are number of electrons and holes per unit volume. μ_n and μ_p are the mobilities of electrons and holes respectively, e is charge of electrons and E is electric field.

So total drift current density $J = J_n(\text{drift}) + J_p(\text{drift})$

$$J = n\mu_n eE + p\mu_p eE$$

For Intrinsic semiconductor

$$J = n_i e(\mu_n + \mu_p)E$$

Diffusion current

Definition: the non-uniform distribution of charge carriers creates the regions of uneven concentrations in the semiconductor.

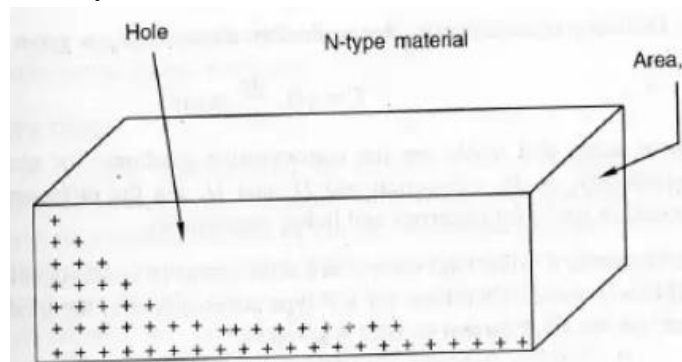
The charge carriers move from the regions of higher concentration to the regions of lower concentration. This process is known as diffusion. The current is known as diffusion current. Consider a semiconductor having a concentration gradient of electrons $\frac{dn}{dx}$ within the semiconductor. The electrons diffuse from high concentration to low concentration due to the concentration gradient.

$$\text{Rate of flow of electrons through unit area} \propto - \left(\frac{dn}{dx} \right)$$

Here negative sign denotes that the electrons are diffusing from higher concentration to lower concentration region.

$$\text{Rate of flow of electrons through unit area} = -D_n \left(\frac{dn}{dx} \right)$$

Where D_n is a proportionality constant and it is known as diffusion coefficient of electrons.



$$\text{Rate of flow of electrons through unit area} = -e \times -D_n \left(\frac{dn}{dx} \right)$$

Rate of flow of electrons through unit area is the diffusion current density of electrons

$$J_n(\text{diffusion}) = e D_n \left(\frac{dn}{dx} \right)$$

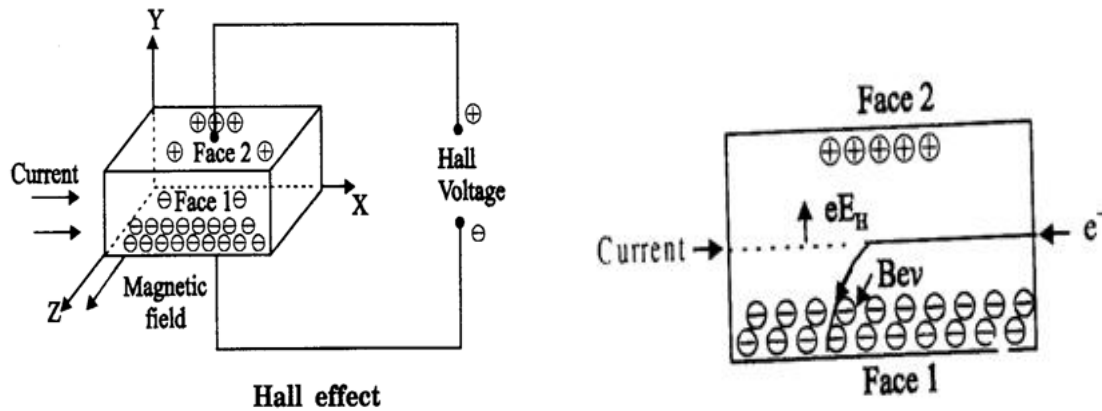
Similarly, the diffusion current density of holes is given by $J_p(\text{diffusion}) = -e D_p \left(\frac{dp}{dx} \right)$

Where D_p is diffusion constant of holes.

Hall Effect

Hall Effect is used to distinguish between the two types of charge carriers. It is also used to determine the charge carrier densities and the mobility of charge carriers.

Statement: When a conductor (metal or semiconductor) carrying a current (I) is placed in a perpendicular magnetic field (B), a potential difference (electric field) is produced inside the conductor in a direction normal to the directions of both the current and the magnetic field.



Hall effect in n-type semiconductor:

Let us consider a n-type semiconductor material in the form of rectangular slab. In such a material current flows in the X-direction, magnetic field B is applied in the Z direction. As a result Hall voltage is developed along Y-direction. The current flow is entirely due to the flow of electrons moving from right to left. When a magnetic field is applied, the electrons moving with velocity v will experience a downward force Bev .

Where $B \rightarrow$ Applied magnetic field

$e \rightarrow$ Charge of an electron

The downward force deflects the electrons in downward direction and therefore there is an accumulation of negatively charged electrons on the bottom face of the slab.

\therefore A potential difference is established between top and bottom of the specimen. This potential difference causes an electric field E_H called Hall field. This field will give rise to a force eE_H acting in the upward direction on each electron.

At equilibrium, downward force Bev will balance the upward force eE_H .

$$\therefore Bev = eE_H$$

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$$E_H = Bv \quad \dots\dots(1)$$

The current density $J_x = nev$

$$\therefore v = -\frac{J_x}{ne} \quad \dots\dots(2)$$

Where $n \rightarrow$ concentration of current carrier (electrons)

Substitute equation (2) in (1) we have

$$E_H = -\frac{BJ_x}{ne} \quad \dots\dots(3)$$

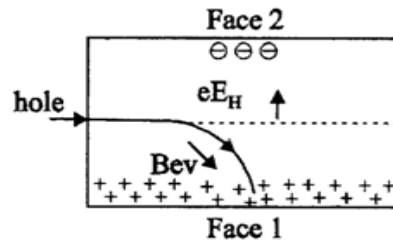
$$E_H = R_H J_x B \quad \dots\dots(4)$$

$$\therefore R_H = \frac{E_H}{J_x B}$$

$$\text{Where } R_H = -\frac{1}{ne} \quad \dots(5)$$

Where $R_H \rightarrow$ Hall coefficient or Hall constant.

Hall effect in p type semiconductor:



Hall effect in p-type semiconductor

Consider a rectangular slab of p-type semiconducting material and the current flow in this case is entirely due to the flow of positive holes from left to right. The current flow is along x- direction and the magnetic field is applied in the z- direction. Due to applied magnetic field, the holes are accumulated in the bottom of the slab and thus produce a potential difference.

$$\text{Hall coefficient can be written as } R_H = +\frac{1}{p_e} \quad \dots\dots(6)$$

Where $p \rightarrow$ Concentration of current carriers(holes)

Hall coefficient in terms of Hall voltage:

$$\text{If } t \text{ is the thickness of the sample and } V_H \text{ is the Hall voltage, then } V_H = E_H t \quad \dots(7)$$

Where E_H is the Hall field

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Substitute equation (4) in (7) we $V_H = R_H J_x B t$ (8)

If b is the breadth of the sample, then Area of the sample (A) = Breadth (b) x Thickness (t)
= bt

$$\text{Current density } J_x = \frac{I_x}{\text{Area of the sample (A)}} \quad J_x = \frac{I_x}{bt} \quad \text{.....(9)}$$

Substituting equation (9) in (8) we have $V_H = \frac{R_H I_x B t}{bt}$

$$\therefore V_H = \frac{R_H I_x B}{b}$$

$$\text{Hall coefficient, } R_H = \frac{V_H b}{I_x B} \quad \text{.....(10)}$$

Mobility of charge carriers:

Electrical conductivity of a n-type semiconductor $\sigma_e = n e \mu_e$

$$\therefore R_H = \frac{-1}{ne} \quad \text{..... (11)}$$

Where $\mu_e \rightarrow$ mobility of charge carriers (electrons)

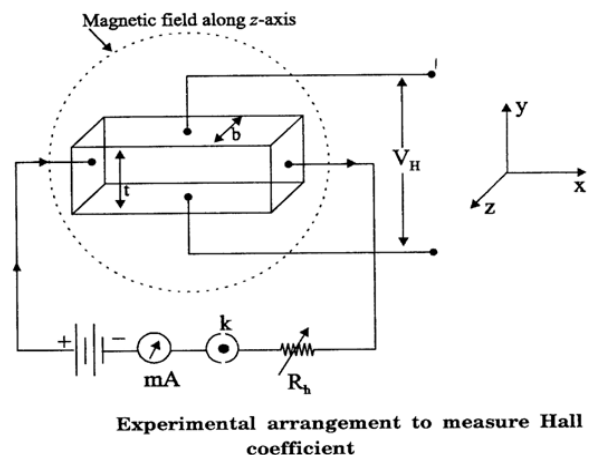
Electrical conductivity of a p-type semiconductor $\sigma_h = p e \mu_h$

$$\therefore R_H = \frac{-1}{pe} \quad \text{..... (12)}$$

Where $\sigma_h \rightarrow$ mobility of charge carriers(holes)

Determination of Hall coefficient:

A semiconductor material is taken in the form of a rectangular slab of thickness t and breadth b. A suitable current I_x ampere is allowed to pass through this sample along x- axis by connecting it to a battery. The sample is placed in between two poles of an electromagnet such that the applied magnetic field is along the z-axis ie, perpendicular to the plane of paper.



Hall voltage V_H is developed in the sample is measured by fixing two probes at the centres of the bottom and top faces of the sample. By

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measuring Hall voltage, hall coefficient is determined from the formula

$$R_H = \frac{V_H b}{I_x B}$$

Applications of Hall Effect:

(i) **Determination of semiconductor type:** the sign of the hall coefficient is used to find whether a given semiconductor is n-type or p-type.

(ii) **Calculation of carrier concentration:** by measuring hall coefficient R_H , carrier concentration is determined from the relation $n = \frac{1}{e R_H}$

(iii) **Determination of mobility:** we know that electrical conductivity

$$\sigma_e = ne\mu_e \quad \mu_e = \frac{\sigma_e}{ne} \quad \mu_e = \sigma_e R_H$$

(iv) **Magnetic field meter:** Hall voltage V_H for a given current is proportional to B. Hence V_H measures the magnetic field B.

(v) **Hall effect multiplier:** It can give an output proportional to the product of two signals. If current I proportional to one input and if B proportional to the second input, then V_H is proportional to the product of two inputs.

Hall Devices

The devices which uses the Hall Effect for its applications is known as hall device. There are 3 types of hall devices.

1. Gauss meter
2. Electronic Multiplier
3. Electronic Wattmeter

a) Gauss meter

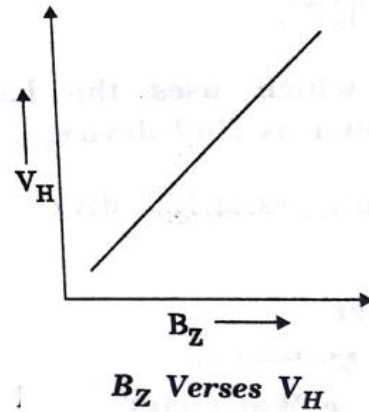
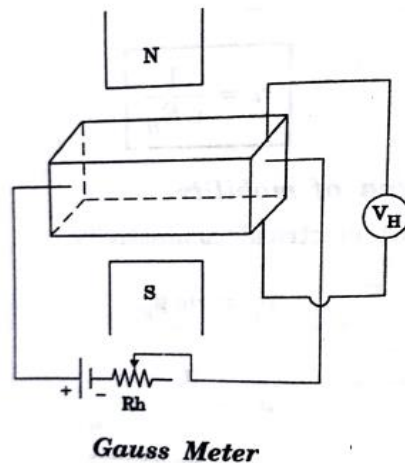
The hall voltage $V_H = \frac{R_H B_Z I_x}{t}$. In this $V_H \propto B_Z$ for a given hall element; R_H and t are constant.

The current I through Hall element is also kept constant.

This principle is used in Gauss meter. It is used for measuring magnetic field. The variation of Hall voltage with magnetic field is shown in fig. the voltmeter which is used to measure V_H can be

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directly calibrated in terms of gauss. The graph can also be used to measure any unknown magnetic fields.



b) Electronic Multipliers

From Hall Effect, we have

$$V_H = \frac{R_H B_Z I_1}{t}$$

Since R_H and t are constant for an element.

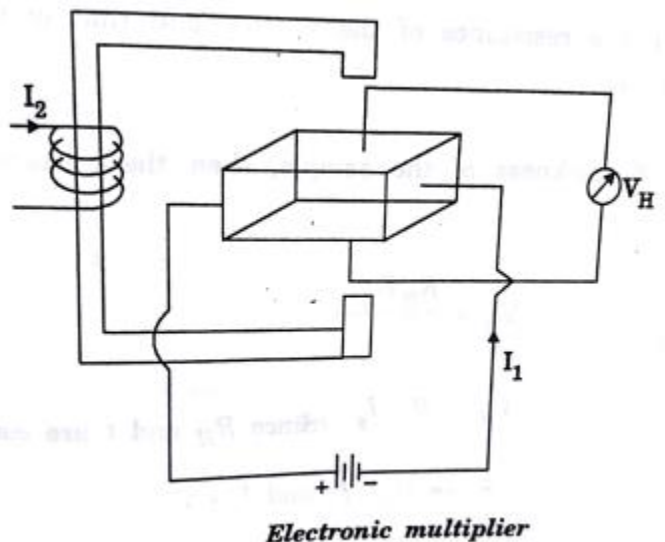
$$V_H = B_Z I_1$$

But, the magnetic field B_Z is proportional to current (I_2) through the coil.

$$\text{i.e.; } B_Z \propto I_2$$

$$\therefore V_H \propto I_1 I_2$$

V_H is a measure of the product of two currents. This is the basic principle used in analog electronic multipliers.



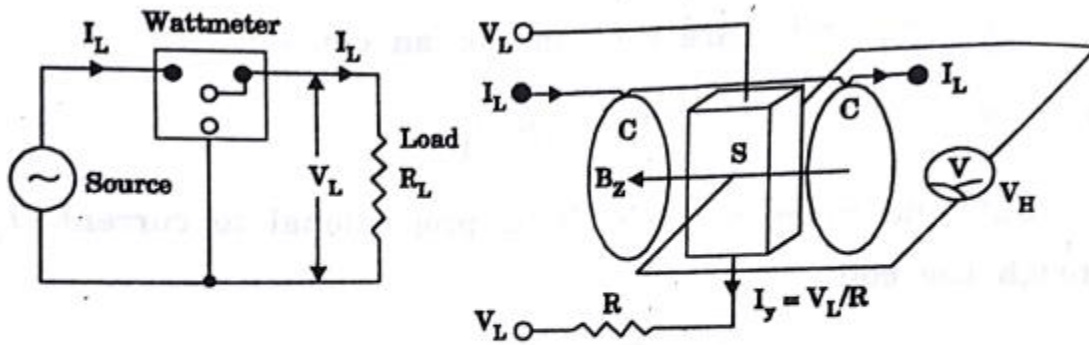
c) Electronic Wattmeter

Hall Effect is used to measure electrical power dissipated in a load. The instrument used to measure the power in a circuit using Hall Effect principle is known as Hall Effect – Watt meter. S

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is Hall Effect sample. It is placed in a magnetic field B_Z produced by the load current I_L passing through the coils CC.

The voltage across the load V_L drives the current $I_y = \frac{V_L}{R}$ through the sample. R is a series resistance which is \gg than the resistance of the sample and that of the load. Also $I_y \ll I_L$



V_L - Load voltage I_L - Load Current C, C - Coils to set magnetic field B

Hall effect wattmeter

If “ t ” thickness of the sample, then the measured hall voltage

$$V_H = \frac{R_H B_Z I_y}{t}$$

$$V_H \propto B_Z I_y \text{ (Since } R_H \text{ and } t \text{ are constant).}$$

$$\text{Since } B_Z \propto I_L \text{ and } I_y \propto V_L \quad V_H \propto V_L I_L$$

This is the electric power dissipated by the load. The voltmeter that measures V_H can be calibrated directly to read power.

Metal – Semiconductor Contact

Metal – semiconductor contact plays a very important role in the present day electronics devices and integrated circuit technology.

When a metal and a semiconductor are brought into contact, there are 2 types of junctions formed depending on the work functions of the metal and semiconductor.

Types of Metal – Semiconductor junction

(i) Schottky junction - $\phi_m > \phi_{semi}$

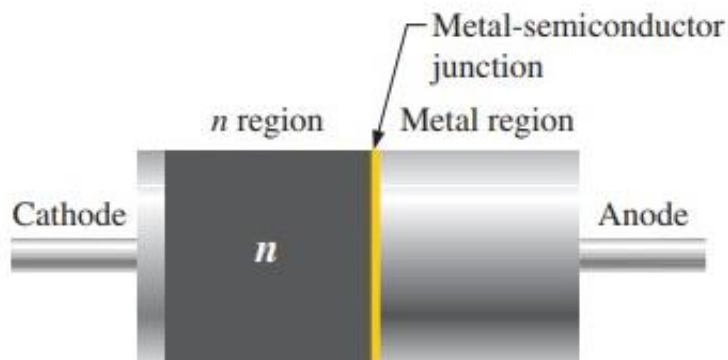
(ii) Ohmic junction - $\phi_m < \phi_{semi}$

Work function: energy required to raise the electron from the metal or the semiconductor to the vacuum level.

Schottky Diode

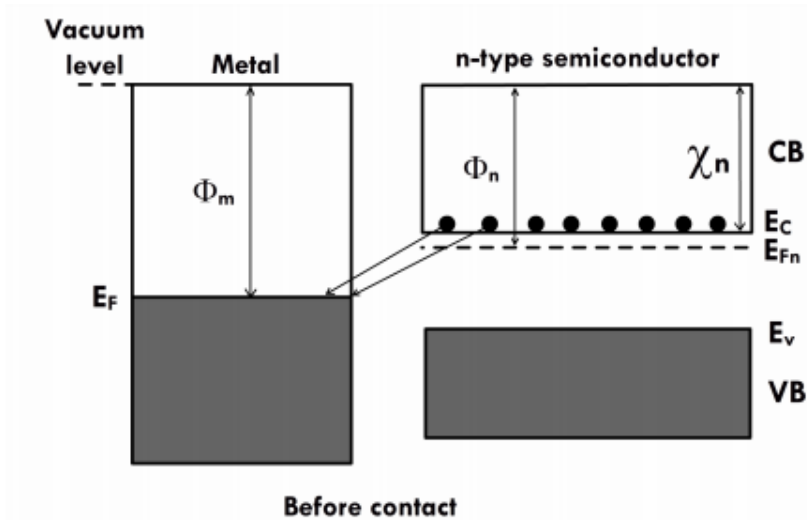
When the metal has high work function than that of n-type semiconductor then the junction formed is called Schottky diode.

Principle: Schottky diode is a unilateral device in which current flows from metal to semiconductor (n-type) in one direction.

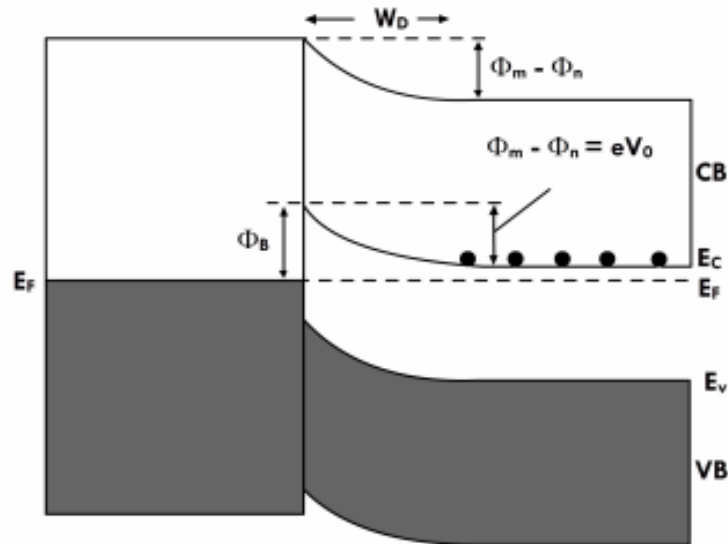


Schottky Diode Symbol

Consider a junction formed between a metal and n-type semiconductor. The Fermi level of the semiconductor is higher (since its work function is lower) than the metal. The electrons in the conduction level of the semiconductor move to the empty energy states above the Fermi level of the metal. This leaves a positive charge on the semiconductor side and due to the excess electrons, a negative charge on the metal side, leading to a contact potential.



When a Schottky junction is formed between the metal and semiconductor, the Fermi level lines up and also a positive potential is formed on the semiconductor side. Because the depletion region extends within a certain depth in the semiconductor there is bending of the energy bands on the semiconductor side. Bands bend up in the direction of the electric field.



The Schottky junction can be biased by application of an external potential.

There are two types of bias

1. Forward bias - metal is connected to positive terminal and n-type semiconductor connected to negative terminal

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- Reverse bias - metal is connected to negative terminal and n-type semiconductor connected to positive terminal

The current flow depends on the type of bias and the amount of applied external potential.

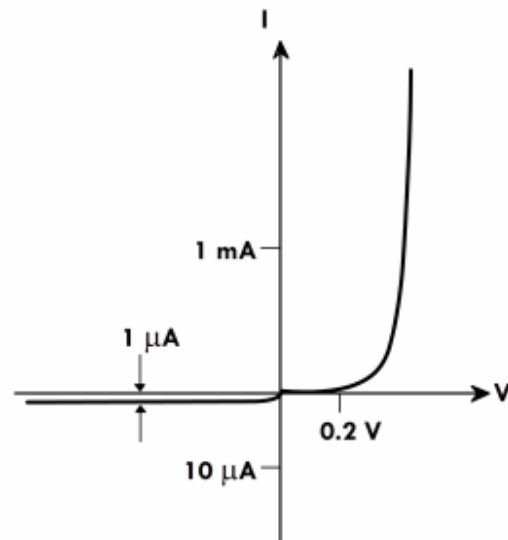
Forward bias:

In a forward biased Schottky junction the external potential is applied in such a way that it opposes the in-built potential. The electrons injected from the external circuit into the n-type semiconductor have a lower barrier to overcome before reaching the metal. This leads to a current in the circuit which increases with increasing external potential.

Reverse bias:

In the case of a reverse bias the external potential is applied in the same direction as the junction potential. This increases the width of depletion region further and hence there is no flow of electron from semiconductor to metal. So a Schottky junction acts as a rectifier i.e. it conducts in forward bias but not in reverse bias

The I – V characteristics of the junction is shown in figure. There is an exponential increase in current in the forward bias (I quadrant) while there is a small current in reverse bias.



Advantages of Schottky diode

- In Schottky diode, stored charges or depletion region is negligible. So a Schottky diode has a very low capacitance.
- The Schottky diode will immediately switch from ON state to OFF state since the depletion region is negligible.
- A small voltage is enough to produce large current.
- It has high efficiency.
- It operates at high frequencies.
- It produces less noise.

Applications of Schottky diode

- It can be used for rectification of signals of frequencies even exceeding 300 MHz.

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- It is commonly used in switching device at frequencies of 20GHz.
- It is used in radio frequency applications.
- It is widely used in power supplies.
- It is used in logic circuits.
- Its low noise figure finds application in sensitive communication receivers like radars.
- It is also used in clipping and clamping circuits and in computer grating.

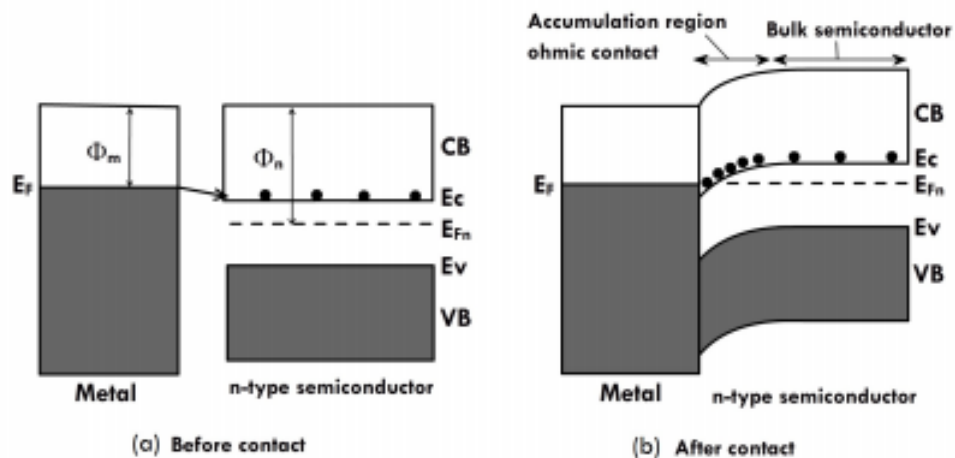
Ohmic Contacts

When the semiconductor has a higher work function the junction formed is called the Ohmic junction.

Principle: An Ohmic contact is a non-rectifying contact which obeys Ohm's law ($V=IR$). The resistance of the Ohmic contact should always be low i.e., conductivity should be large.

Here, the current is conducted equally in both directions and there is a very little voltage drop across the junction. Before contact, fermi level of the metal and semiconductor are at different positions.

At equilibrium, electrons move from the metal to the empty states in the conduction band so that there is an accumulation region near the interface (on the semiconductor side) from the metal to the empty states in the conduction band so that there is an accumulation region near the interface (on the semiconductor side).



Applications

The use of Ohmic contacts is to connect one semiconductor device to another, an IC, or to connect an IC to its external terminals.

PROBLEMS

1. Find the resistance of an intrinsic Ge rod 1 cm long, 1 mm wide and 0.5 mm thick at 300 K. For Ge, $n_i = 2.5 \times 10^{19}/\text{m}^3$, $0.39 \text{ m}^2\text{V}^{-1} \text{ s}^{-1}$ and $0.19 \text{ m}^2\text{V}^{-1} \text{ s}^{-1}$ at 300 K.

Given:

$$n_i = 2.5 \times 10^{19}/\text{m}^3, \mu_e = 0.39 \text{ m}^2\text{V}^{-1} \text{ s}^{-1}, \mu_h = 0.19 \text{ m}^2\text{V}^{-1} \text{ s}^{-1}, e = 1.6 \times 10^{-19} \text{ J}$$

$$l = 1 \text{ cm} = 1 \times 10^{-2} \text{ m}, \text{ Width} = 1 \text{ mm}, \text{ thickness} = 0.5 \text{ mm}$$

$$\text{Conductivity } \sigma = n_i e (\mu_e + \mu_h)$$

$$\sigma = 2.5 \times 10^{19} \times 1.6 \times 10^{-19} (0.39 + 0.19)$$

$$\sigma = 2.32 \Omega^{-1} \text{ m}^{-1}$$

$$\text{Area} = \text{width} \times \text{thickness} = 1 \times 10^{-3} \times 0.5 \times 10^{-3}$$

$$R = \frac{l}{\sigma A} = \frac{1 \times 10^{-2}}{2.32 \times (1 \times 10^{-3} \times 0.5 \times 10^{-3})}$$

$$R = 8620.6 \Omega$$

2. The intrinsic carrier density is $1.5 \times 10^{16}/\text{m}^3$. If the mobility of electron and hole are 0.13 and $0.05 \text{ m}^2\text{V}^{-1} \text{ s}^{-1}$ calculate the conductivity.

$$\text{Given: } n_i = 1.5 \times 10^{16}/\text{m}^3, \mu_e = 0.13 \text{ m}^2\text{V}^{-1} \text{ s}^{-1}, \mu_h = 0.05 \text{ m}^2\text{V}^{-1} \text{ s}^{-1}$$

$$\sigma = n_i e (\mu_e + \mu_h)$$

$$\sigma = 15 \times 10^{16} \times 1.6 \times 10^{-19} (0.13 + 0.05)$$

$$\sigma = 4.32 \times 10^{-4} \Omega^{-1} \text{ m}^{-1}$$

3. The donor density of an n-type germanium sample is $10^{21}/\text{m}^3$. The sample is arranged in a Hall experiment having magnetic field of 0.5 Tesla and the current density is 500 ampere/ m^2 . Find the Hall voltage if the sample is 3 mm wide.

$$\text{Given: } n_e = 10^{21}/\text{m}^3, B = 0.5 \text{ Tesla}, t = 3 \text{ mm} = 3 \times 10^{-3} \text{ m}, J_x = 500 \text{ ampere}/\text{m}^2$$

$$R_H = \frac{1}{n_e e}$$

$$R_H = \frac{1}{10^{21} \times 1.6 \times 10^{-19}}$$

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$$R_H = 6.25 \times 10^{-3}$$

$$V_H = R_H J_x B t$$

$$V_H = 6.25 \times 10^{-3} \times 500 \times 0.5 \times 3 \times 10^{-3}$$

$$\text{Hall Voltage } V_H = 4.6875 \times 10^{-3} \text{ Volts}$$

4. In a p-type germanium, $n_i = 2.1 \times 10^{19} \text{ m}^{-3}$, density of boron = $4.5 \times 10^{23} \text{ atoms m}^{-3}$. The electrons and hole mobility are 0.4 and 0.2 $\text{m}^2/\text{volt sec}$ respectively. What is its conductivity before and after the addition of boron atoms?

Given: $n_i = 2.1 \times 10^{19}/\text{m}^3$; $\mu_e = 0.4 \text{ m}^2/\text{volt}$; $\mu_h = 0.2 \text{ m}^2/\text{volt.sec}$

(i) Before including boron atoms, the semiconductor is an intrinsic semiconductor.

Therefore, Conductivity (σ) = $n_i e (\mu_e + \mu_h)$

$$= 2.1 \times 10^{19} \times 1.6 \times 10^{-19} (0.4 + 0.2)$$

$$\sigma = 2.016 \Omega^{-1} \text{ m}^{-1}$$

(ii) After the boron atoms are included, each boron atoms are ready to accept one electron.

Therefore, Conductivity of p type semiconductor after boron atoms are included.

$$\sigma' = p e \mu_h$$

$$\sigma' = 4.5 \times 10^{23} \times 1.6 \times 10^{-19} \times 0.2$$

$$\sigma' = 1.44 \times 10^4 \Omega^{-1} \text{ m}^{-1}$$

5. A n-type semiconductor has Hall coefficient = $4.16 \times 10^{-4} \text{ m}^{-3} \text{ C}^{-1}$. The conductivity is $108 \text{ ohm}^{-1} \text{ m}^{-1}$. Calculate its charge carrier density n_e and electron mobility at room temperature.

Given: $R_H = 4.16 \times 10^{-4} \text{ m}^{-3} \text{ C}^{-1}$, $\sigma = 108 \Omega^{-1} \text{ m}^{-1}$

For n-type the charge carrier density is $n_e = -\frac{1}{e R_H}$

$$n_e = \frac{3\pi}{8} \frac{1}{e R_H}$$

$$n_e = \frac{3 \times 3.14}{8} \frac{1}{1.6 \times 10^{-19} \times 4.16 \times 10^{-4}}$$

$$n_e = 1.7690 \times 10^{22} / \text{m}^3.$$

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i) Electron mobility $\mu_e = \frac{\sigma_e}{n_e e}$

$$\mu_e = \frac{108}{1.769 \times 10^{22} \times 1.6 \times 10^{-19}}$$

$$\mu_e = 0.03816 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$$

6. The Hall co-efficient of certain silicon was found to be $-7.35 \times 10^{-5} \text{ m}^3\text{C}^{-1}$ from 100 to 400 K. Determine the nature of the semiconductor. If the conductivity was found to be $200 \text{ m}^{-1} \Omega^{-1}$, calculate the density and mobility of the charge carriers.

Since Hall coefficient is negative the given semiconductor is an 'n' type semiconductor.

For an n-type semiconductor, Conductivity $\sigma = n_e e \mu_e$

$$\text{Mobility } \mu_e = \frac{\sigma}{n_e e}$$

$$\text{Here } n_e = -\frac{1}{e R_H} \quad n_e = -\frac{1}{1.6 \times 10^{-19} \times -7.35 \times 10^{-5}}$$

$$\text{Charge density of electrons } n_e = 8.503 \times 10^{22} / \text{m}^3$$

$$\text{Therefore } \mu_e = \frac{200}{8.503 \times 10^{22} \times 1.6 \times 10^{-19}}$$

$$\text{Mobility of charge carriers } \mu_e = 0.0147 \text{ m}^2\text{V}^{-1}\text{s}^{-1}.$$

7. The energy gap of Si is 1.1 eV. Its electron and hole mobilities at room temperature are 0.48 and $0.013 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$. Evaluate its conductivity.

$$\mu_e = 0.48 \text{ m}^2\text{V}^{-1}\text{s}^{-1} \quad \mu_h = 0.013 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$$

$$n_i = 2 \left[\frac{2\pi m_e k_B T}{h^2} \right] \exp \frac{-E_g}{2k_B T}$$

$$n_i = 2 \left[\frac{2 \times 3.14 \times 9.11 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300}{(6.625 \times 10^{-34})^2} \right] \exp \frac{-1.1 \times 1.6 \times 10^{-19}}{2(1.38 \times 10^{-23} \times 300)}$$

$$n_i = 1.4707 \times 10^{16} / \text{m}^3$$

$$\text{Conductivity } \sigma = n_i e (\mu_e + \mu_h)$$

$$\sigma = 1.4707 \times 10^{16} \times 1.6 \times 10^{-19} \times (0.48 + 0.013)$$

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$$\sigma = 1.160 \times 10^{-3} \Omega^{-1} \text{m}^{-1}.$$

8. A patient with a pacemaker is mistakenly being scanned for an MRI image. A 10 cm long section of pacemaker wire moves at a speed of 10 cm/s perpendicular to the MRI unit's magnetic field and a 20mV Hall voltage is induced. What is the magnetic field strength?

Length of the path $l = 10 \text{ cm} = 0.1 \text{ m}$, Velocity $V = 10 \text{ cm/s} = 0.1 \text{ m/s}$

Induced voltage $V = 20 \text{ mV} = 20 \times 10^{-3} \text{ V}$

Induced Hall voltage $V = Bvl$

$$B = \frac{V}{vl}$$

$$B = \frac{20 \times 10^{-3}}{0.1 \times 0.1}$$

$$B = 2 \text{ Tesla}$$

9. The Hall Co-efficient of a specimen of doped silicon is found to be $3.66 \times 10^{-4} \text{ m}^3/\text{C}$. The resistivity of specimen is $8.93 \times 10^{-3} \Omega \text{m}$. Find the mobility and density of charge carriers.

$$\text{Charge carrier density } n_e = \frac{3\pi}{8} \frac{1}{eR_H}$$

$$n_e = \frac{3 \times 3.14}{8} \frac{1}{1.6 \times 10^{-19} \times 3.66 \times 10^{-4}}$$

$$n_e = 2.0107 \times 10^{22} / \text{m}^3$$

$$\text{Electron mobility } \mu_e = \frac{\sigma_e}{n_e e} \mu_e = \frac{1}{\rho_e n_e e}$$

$$\mu_e = \frac{1}{8.93 \times 10^{-3} \times 2.0107 \times 10^{22} \times 1.6 \times 10^{-19}}$$

$$\mu_e = 0.0348 \text{ m}^2/\text{Vs}.$$

10. A silicon plate of thickness 1mm, breadth 10 mm and length 100 mm is placed in a magnetic field of 0.5 Wb/m^2 acting perpendicular to its thickness. If 10^{-2} A current flows

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along its length, calculate the Hall voltage developed, if the Hall coefficient is 3.66×10^4 m³/coulomb.

$$V_H = \frac{R_H I_H B}{t} \quad V_H = \frac{3.66 \times 10^{-4} \times 10^{-2} \times 0.5}{1 \times 10^{-3}} \quad V_H = 1.83 \times 10^{-3} \text{ Volts.}$$

UNIT III -MAGNETIC PROPERTIES OF MATERIALS

1. INTRODUCTION

Any materials that can be magnetized by an applied external magnetic field is called a magnetic materials. Magnetic materials can be easily magnetized because they have permanent or induced magnetic moment in the presence of applied magnetic field. Magnetism arise from the magnetic moment or magnetic dipole of the magnetic materials. Among the different eleven types of magnetic materials, only five magnetic materials are the most important for the practical application. They are:

- Diamagnetic materials.
- Paramagnetic materials.
- Ferromagnetic materials.
- Antiferromagnetic materials.
- Ferrimagnetic materials or ferrites.

2 TERMS AND DEFINITIONS

Magnetic flux (ϕ)

Total number of magnetic lines of force passing through a surface is known as magnetic flux. It is represented by the symbol ' ϕ ' and its unit

Magnetic flux density (or) Magnetic induction (B)

Magnetic flux density at any point in a m passing normally through unit area of cross section (A) at that point. It is denoted by the symbol B and its unit is weber / metre² or tesla.

$$B = [\phi / A]$$

Intensity of magnetization (I)

The term magnetization means the process of converting non-magnetic material on magnetic material.

When some amount of external magnetic field is applied to the metals such as iron, steel and alloys etc., they are magnetized to different degrees. The intensity of magnetisation (I) is the measure of the magnetisation of a magnetized specimen. It is defined as the magnetic moment per unit volume.

$$I = M / V \text{ weber / metre}^2$$

Magnetic field intensity (or) strength (H)

Magnetic field intensity at any point in a magnetic field is the force experienced by unit north pole placed at that point. It is denoted by H and its unit is Newton per weber or ampere turns per metre (A/m).

Magnetic permeability (μ)

Magnetic permeability of a substance measure the degree to which the magnetic field can penetrate through the substance. It is found that magnetic flux density (B) is directly proportional to the magnetic field strength (H)

$$B \propto H$$

$$B = \mu H$$

Where μ_0 is a constant of proportionality and it is known as permeability or absolute permeability of the medium.

$$\mu = B / H$$

Hence, the permeability of a substance is the ratio of the magnetic flux density (B) inside the substance to the magnetic field intensity (H).

Absolute permeability

Absolute permeability of a medium or material is defined as the product of permeability of free space (μ_0) and the relative permeability of the medium (μ_r)

$$\mu = \mu_0 \times \mu_r$$

Relative permeability of medium (μ_r)

Relative permeability of a medium is defined as the ratio between absolute permeability of a medium to the permeability of a free space

$$\mu_r = \mu / \mu_0$$

Magnetic susceptibility (χ)

Magnetic susceptibility (χ) of a specimen magnetized in a magnetic field.

It is the ratio of intensity of magnetisation (I) induced in it to the magnetizing field (H).

$$\chi = I / H$$

Retentivity (or) Remanence

When the external magnetic field is applied to a magnetic material is removed, the magnetic material will not lose its magnetic property immediately. There exists some residual intensity of magnetization in the specimen even when the magnetic field is cut off. This is called residual magnetism (or) retentivity.

Coercivity

The residual magnetism can be completely removed from the material by applying a reverse magnetic field. Hence coercivity of the magnetic material is the strength of reverse magnetic field ($-H_c$) which is used to completely demagnetize the material.

3 ORIGIN OF MAGNETIC MOMENT AND BOHR MAGNETON

Origin of magnetic moment

Any matter is basically made up of atoms. The property of magnetism exhibited by certain materials with the magnetic property of its constituent atoms. We know that electrons in an atom revolve around the nucleus in different orbits.

Basically there are three contributions for the magnetic dipole moment of an atom.

The orbital motions of electrons (the motion of electrons in the closed orbits around the nucleus) are called orbital magnetic moment.

Spin motion of the electrons (due to electron spin angular momentum) is called spin magnetic moment.

The contribution from the nuclear spin (due to nuclear spin angular momentum) is nearly 10^{-3} times smaller than that of electron spin; it is not taken into consideration.

Bohr Magnetron

The magnetic moment contributed by an electron with angular momentum quantum number $n =$

1 is known as Bohr Magneton.

4 DIFFERENT TYPES OF MAGNETIC MATERIALS

DIAMAGNETIC MATERIALS

Diamagnetism is exhibited by all the materials. The atoms in the diamagnetic materials do not possess permanent magnetic moment.

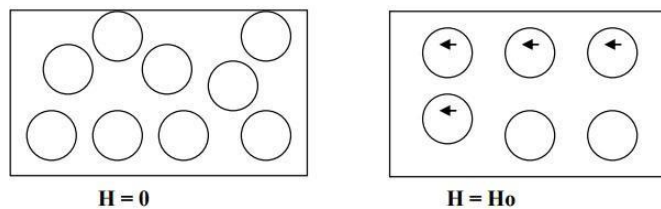
However, when a material is placed in a magnetic field, the electrons in the atomic orbits tend to counteract the external magnetic field and the atoms acquire an induced magnetic moment.

As a result, the material becomes magnetized. The direction of the induced dipole moment is opposite to that of externally applied magnetic field. Due to this effect, the material gets very weakly repelled, in the magnetic field. This phenomenon is known as diamagnetism.

When a magnetic field H_0 is applied in the direction shown in fig., the atoms acquire an induced magnetic moment in the opposite direction to that of the field.

The strength of the induced magnetic moment is proportional to the applied field and hence magnetization of the material varies directly with the strength of the magnetic field.

The induced dipoles and magnetization vanish as soon as the applied field is removed.

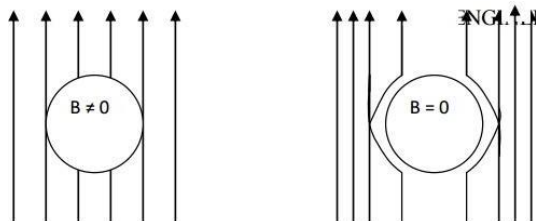


Properties of diamagnetic material

Diamagnetic magnetic material repels the magnetic lines of force. The behaviour of diamagnetic material in the presence of magnetic field.

There is no permanent dipole moment. Therefore, the magnetic effects are very small.

The magnetic susceptibility is negative and it is independent of temperature and applied magnetic field strength.



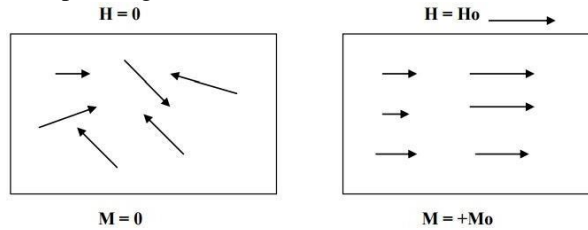
PARAMAGNETIC MATERIALS

In certain materials, each atom or molecule possesses a net permanent magnetic moment (due to orbital and spin magnetic moment) even in the absence of an external magnetic field.

The magnetic moments are randomly oriented in the absence of external magnetic field. Therefore the net magnetic moment is zero, and hence the magnetization of the material is zero.

But, when an external magnetic field is applied, the magnetic dipoles tend to align themselves in the direction of the magnetic field and the material becomes magnetized. As shown in fig. This effect is

known as paramagnetism.



Thermal agitation disturbs the alignment of the magnetic moments. With an increase in temperature, the increase in thermal agitation tends to randomize the dipole direction thus leading to a decrease in magnetization.

This indicates that the paramagnetic susceptibility decreases with increases in temperature. It is noted that the paramagnetic susceptibility varies inversely with temperature.

$$\chi \propto 1/T$$

$$\chi = C/T$$

This is known as Curie law of paramagnetism and C is a constant called Curie constant

Properties of paramagnetic materials

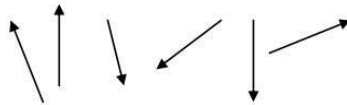
Paramagnetic materials attract magnetic lines of force. They possess permanent dipole moment.

The susceptibility is positive and depend on temperature is given by

$$\chi = C_0 / T$$

The spin alignment is shown in fig.

Example- Manganous sulphate, ferric oxide, ferrous sulphate, nickel sulphate, etc.



FERROMAGNETIC MATERIALS

Certain materials like iron, cobalt, nickel and certain alloys exhibit high degree of magnetization. These materials show spontaneous magnetization. (i.e) they have small amount of magnetization even in the absence of external magnetic field.

This indicates that there is strong internal field within the material which makes atomic magnetic moments with each other. This phenomenon is known as ferromagnetism.

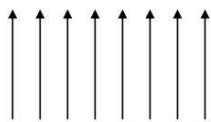
Properties of ferromagnetic materials:

All the dipoles are aligned parallel to each other due to the magnetic interaction between the two dipoles.

They have permanent dipole moment. They are strongly attracted by the magnetic field.

They exhibit magnetization even in the absence of magnetic field. This property of ferromagnetic material is called as spontaneous magnetization.

They exhibit hysteresis curve.



On heating, they lose their magnetization slowly. The dipole alignment is shown in fig.

The susceptibility is very high and depends on the temperature. It is given by

$$\chi = C / (T - \theta)$$

[for $T > \theta$; paramagnetic behaviour;
for $T < \theta$; ferromagnetic behaviour]

Where C is the Curie constant and θ is the paramagnetic Curie temperature.

ANTIFERROMAGNETIC MATERIALS

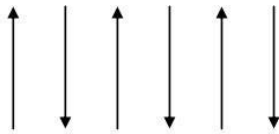
Antiferromagnetic materials are magnetic materials which exhibit a small positive susceptibility of the order of 10^{-3} to 10^{-5} .

In antiferromagnetic materials, the susceptibility increases with increasing temperature and it reaches maximum at a certain temperature called Neel Temperature, T_N .

With further increase in temperature, the material reaches the paramagnetic state. The material is antiferromagnetic below T_N .

Properties of antiferromagnetic materials

The electron spin of neighboring atoms are aligned antiparallel. (i.e) the spin alignment is antiparallel.



Antiferromagnetic susceptibility is mainly depends on temperature.

The susceptibility of the antiferromagnetic material is small and positive. It is given by

$$\chi = C / T + \theta \quad \text{when } T > T_N$$

$$\chi \propto T \quad \text{when } T < T_N$$

The susceptibility initially increases slightly with the temperature and beyond Neel temperature, the susceptibility decreases with temperature.

FERRIMAGNETIC MATERIALS

Properties of ferrites

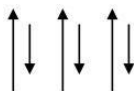
Ferrites have net magnetic moment.

Above Curie temperature, it becomes paramagnetic, while it behaves ferromagnetic material below Curie temperature.

The susceptibility of ferrite is very large and positive. It is temperature dependent and is given by

$$\chi = C / T \pm \theta \quad \text{for } T > T_N$$

Spin alignment is antiparallel of different magnitudes as shown fig.



Mechanically it has pure iron character. They have high permeability and resistivity.

They have low eddy current losses and low hysteresis losses.

5 FERROMAGNETISM

The materials which have finite value of magnetization even if the external magnetic field is absent are called ferromagnetic materials. This phenomenon is called ferromagnetism. The ferromagnetic materials exhibit high degree of magnetization.

Explanation

In a ferromagnetic material, the magnetic interactions between any two dipoles align themselves parallel to each other. Ferromagnetism arises due to the special form of interaction called exchange coupling between adjacent atoms. This exchange coupling is favourable for spin alignment and they coupling their magnetic moments together in rigid parallelism.

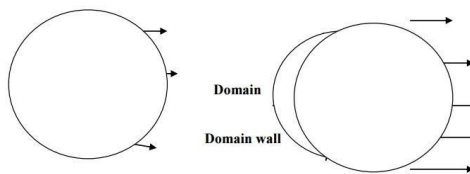
A ferromagnetic materials exhibits ferromagnetic property below a particular temperature called ferromagnetic. Curie temperature (θ_c). Above θ_c they behaves as paramagnetic material.

6. DOMAIN THEORY OF FERROMAGNETISM

We can observe that ferromagnetic materials such as iron does not have magnetization unless they have been previously placed in an external magnetic field. But according to Weiss theory, the molecular magnets in the ferromagnetic material are said to be aligned in such way that, they exhibit magnetization even in the absence of external magnetic field. This is called spontaneous magnetization. (i.e) it should have some internal magnetization due to quantum exchange energy.

According to Weiss hypothesis, a single crystal of ferromagnetic material is divided into large number of small regions called domains. These domains have spontaneous magnetization due to the parallel alignment of spin magnetic moments in each atom. But the direction of spontaneous magnetization varies from domain to domain and is oriented in such way that the net magnetization of the specimen is zero

The boundaries separating the domains are called domain walls. These domain walls are analogous to the grain boundaries in a polycrystalline material.



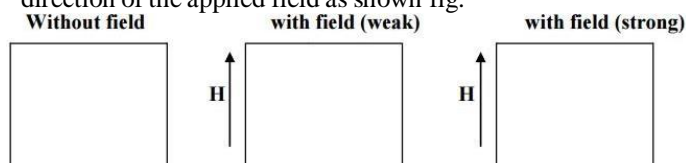
DOMAIN MAGNETIZATION

Now when the magnetic field is applied, then the magnetization occurs in the specimen by two ways
By moment of domain walls By rotation of domain walls **moment of domain walls**

The moment of domain walls takes place in weak magnetic fields. Due to this weak field applied to the specimen the magnetic moment increases and hence the boundary of domains displaced, so that the volume of the domains changes as shown in fig.

By rotation of domain walls

The rotation of domain walls takes place in strong magnetic fields. When the external field is high then the magnetization changes by means of rotation of the direction of magnetization towards the direction of the applied field as shown fig.



ENERGIES INVOLVED IN DOMAIN GROWTH

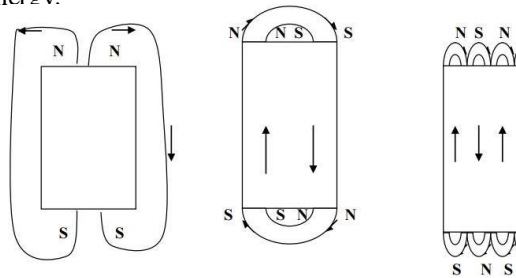
To study the domain structure clearly, we must know four types of energy involved in the process of domain growth. They are

- Exchange energy
- Anisotropy energy
- Domain wall energy
- Magneto-strictive energy

Exchange energy (or) magnetic field energy (or) magneto-static energy

The interacting energy which makes the adjacent dipoles to align themselves is known as exchange energy (or) magnetic field energy. The exchange energy has established a single domain in a specimen of ferromagnetic and it is shown in fig.

It is the energy required in assembling the atomic magnets in a single domain and this work done is stored as potential energy.



Anisotropy energy

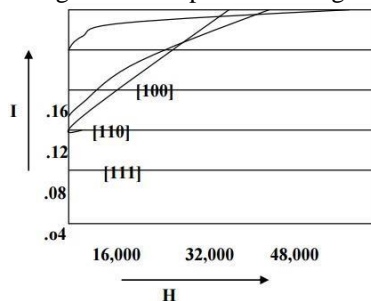
In ferromagnetic crystals there are two directions of magnetization. Easy direction

Hard direction

In easy direction of magnetization, weak field can be applied and in hard direction of magnetization, strong field should be applied. For producing the same saturation magnetization along both hard and easy direction, strong fields are required in the hard direction than the easy direction.

For example in iron easy direction is [100], medium direction is [110] and the hard direction is [111] and it is shown in fig. From the fig we can see that very strong field is required to produce magnetic saturation in hard direction [111] compared to the easy direction [100].

Therefore the excess of energy required to magnetize the specimen along hard direction over that required to magnetize the specimen along easy direction is called crystalline anisotropy energy.



Domain wall energy (or) Bloch wall energy

Domain wall is a transition layer which separates the adjacent domains, magnetized in different directions. The energy of domain wall is due to both exchange energy and anisotropy energy.

Based on the spin alignment, two types of domain walls may arise, namely

Thick wall

Thin wall

(i) Thick wall

When the spin at the boundary are misaligned if the direction of the spin changes gradually as shown in fig, it leads to a thick domain wall. Here the misalignments of spins are associated with exchange energy.

(ii) Thin wall

When the spin at the boundaries changes abruptly, then the anisotropy energy becomes very less. Since the anisotropy energy is directly proportional to the thickness of the wall, this leads to a thin Bloch wall.

Magnetostriuctive energy

When the domains are magnetized in different directions, they will either expand (or) shrink.

Therefore there exists a deformation (i.e) change in dimension of the material, when it is magnetized.

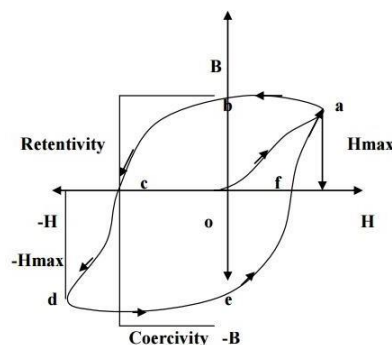
This phenomenon is known as magnetostriction and the energy produced in this effect is known as magnetostriction energy.

The deformation is different along different crystal directions and the change in dimension depends upon the nature of the material.

EXPLANATION OF HYSTERESIS BASED ON DOMAIN THEORY Hysteresis

When a ferromagnetic material is made to undergo through a cycle of magnetization, the variation of magnetic induction (B) with respect to applied field (H) can be represented by a closed hysteresis loop (or) curve. (i.e) it refers to the lagging of magnetization behind the magnetizing field.

If magnetizing field (H) is applied to a ferromagnetic material and if H increases to H_{max} the material acquires magnetism. So the magnetic induction also increases, represented by oa in the fig.



Now if the magnetic field is decreased from H_{max} to zero, the magnetic induction will not fall rapidly to zero, but falls to 'b' rather than removed, the material still acquires some magnetic induction (ob) which is so called residual magnetism or retentivity.

Now, to remove the residual magnetism, the magnetic field strength is reversed and increased to –

H_{max} represented as ' H_c ' so called coercivity- H) is reduced to zero and the corresponding curve 'de' is obtained. curve 'efa' is obtained.

We know when the ferromagnetic material is subjected to external field, there is an increase in the value of the magnetic moment due to two process.

The moment of domain walls Rotation of domain walls.

When small external field is applied, the domains walls displaced slightly in the easy direction of magnetization. This gives rise to small magnetization corresponding to the initial portion of the hysteresis curve (OA) as shown in fig.

Now of the field is removed, then the domains returns to the original state, and is known as reversible domains.

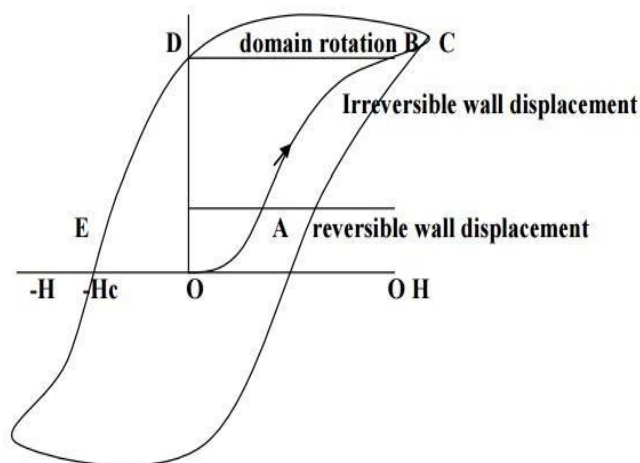
When the field is increased, large numbers of domains contribute to the magnetization and thus the magnetization increases rapidly with H .

Now, even when the field is removed, because of the displacement of domain wall to a very large distance, the domain boundaries do not come back to their original position. This process is indicating as AB in fig and these domains are called irreversible domains.

Now, when the field is further increased, the domains starts rotating along the field direction and the anisotropic energy stored in the hard direction, represented as BC in the fig.

Thus the specimen is said to attain the maximum magnetization. At this position, even when the field is removed the material posses maximum magnetization, called residual magnetism or retnivity, represented by OD in fig.

Actually after the removal of external field, the specimen will try to attain the original configuration by the moment of domain wall. But this moment is stopped due to presence of impurities, lattice imperfections etc. therefore to overcome this; a large amount of reverse magnetic field is applied to the specimen. The amount of energy spend to reduce the magnetization to zero is called coercivity represented by OE in the fig.



It is the loss of the energy in taking a ferromagnetic specimen through a complete cycle of magnetization and the area enclosed is called hysteresis loop.

7 SOFT AND HARD MAGNETIC MATERIALS

Depending upon the direction of magnetization by external field, and the area of hysteresis, magnetic can be classified into two types as,

TYPES OF MAGNETIC MATERIALS

Magnetic materials are classified into two types.

Soft magnetic materials .

Hard magnetic material

Soft magnetic materials:

Materials which are easy to magnetize and demagnetize are called soft magnetic materials.

Example –pure iron, cast iron, carbon steel, silicon steel, mumetal.

Hard magnetic materials:

Materials which retain their magnetism and are difficult to demagnetize are called hard magnetic materials.

Example –tungsten steel, cobalt steel, alnico, alnico, hypernic

Difference between soft and hard magnetic materials

s.no	Soft magnetic materials	Hard magnetic materials
1.	The magnetic materials can be easily magnetize and demagnetize.	The magnetic materials can not be easily magnetize and demagnetize.
2.	The have high permeability.	The have low permeability.
3.	Magnetic energy stored is not high.	Magnetic energy stored is high.
4.	Low hysteresis loss due to small hysteresis loop area.	Large hysteresis loss due to large hysteresis loop area.
5.	Coercivity and retentivity are small.	Coercivity and retentivity are large.
6.	The eddy current loss is small due to its high resistivity.	The eddy current loss is high due to low resistivity.
7.	The domain walls are easy to move.	The movement of domain wall must be prevented.
8.	They are used in electric motor, generators, transformers, relays, telephone receivers, radar.	They are used in loud speakers, electrical measuring instruments.

s.no Soft magnetic materials

1. The magnetic materials can be easily magnetize and demagnetize.
2. The have high permeability.
3. Magnetic energy stored is not high.
4. Low hysteresis loss due to small hysteresis loop area.
5. Coercivity and retentivity are small.
6. The eddy current loss is small due to its high resistivity.

7. The domain walls are easy to move.
8. They are used in electric motor, generators, transformers, relays, telephone receivers, radar.

Hard magnetic materials

1. The magnetic materials can not be easily magnetize and demagnetize.
2. They have low permeability.
3. Magnetic energy stored is high.
4. Large hysteresis loss due to large hysteresis loop area.
5. Coercivity and retentivity are large.
6. The eddy current loss is high due to its low resistivity.
7. The movement of domain wall must be prevented.
8. They are used in loud speakers and electrical measuring instruments.

8. ENERGY PRODUCT

Definition

The product of residual magnetic induction (B_r) and coercivity (H_c) is called energy product or BH product. It is the important quantity to design powerful permanent magnets. It gives the maximum amount of energy stored in the specimen.

Explanation

The energy required to demagnetize a permanent magnet is given by the area of the hysteresis loop between B_r and H_c . The maximum value of this area $B_r H_c$ is called the energy product.

At C and D the energy product is zero because at C, H value is zero and D, B value is zero. The area occupied by the largest rectangle in demagnetizing curve gives the maximum (BH) value.

The energy product is large for permanent magnets. This value is very much useful to analyze whether the material can be used for magnetic recording.

9. FERRIMAGNETIC MATERIALS - FERRITES Ferrites

Ferrites are compounds of iron oxide with oxides of other components.

The general chemical formula is $X^{2+} Fe^{23+} O_4^{2-}$, where (X^{2+}) is a divalent metal ion such as Fe^{2+} , Mg^{2+} , Ni^{2+} , Co^{2+} , Mn^{2+}

STRUCTURE OF FERRITES

Generally there are two types of structures present in the ferrites. They are Regular spinel and Inverse spinel.

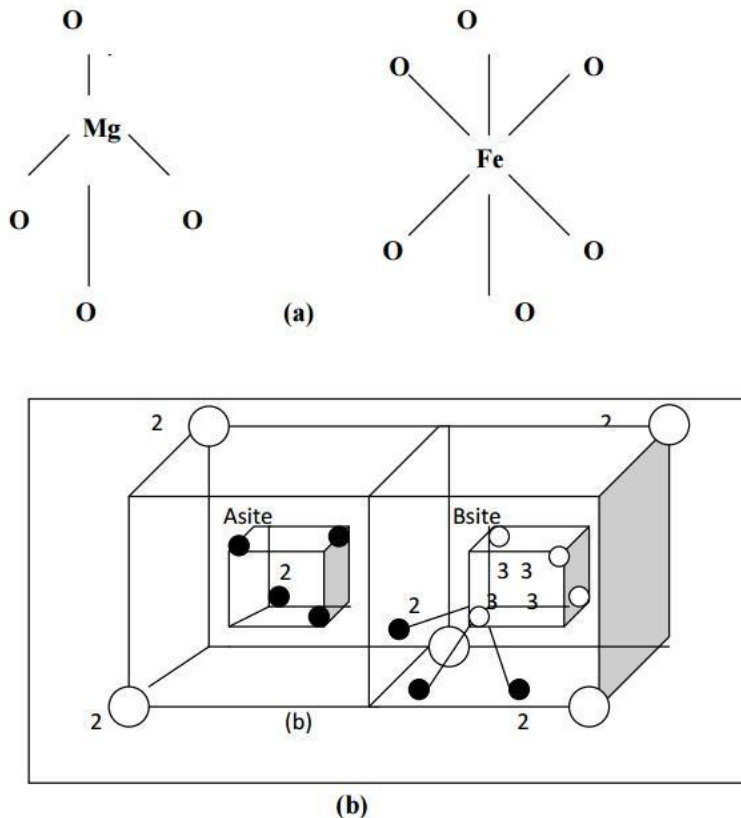
Regular spinel

In regular spinel structure, each divalent metal ion is surrounded by four O^{2-} ions in a tetrahedral fashion.

For example in $Mg^{2+} Fe^{23+} O_4^{2-}$, the structure of Mg^{2+} is given in the fig (a) and it is called A site.

Each Fe^{3+} (trivalent metal ion) is surrounded by six O^{2-} ions and forms an octahedral fashion as shown in fig (a). Totally there will be 16 such octahedral sites in the unit cell. This is indicated by B site.

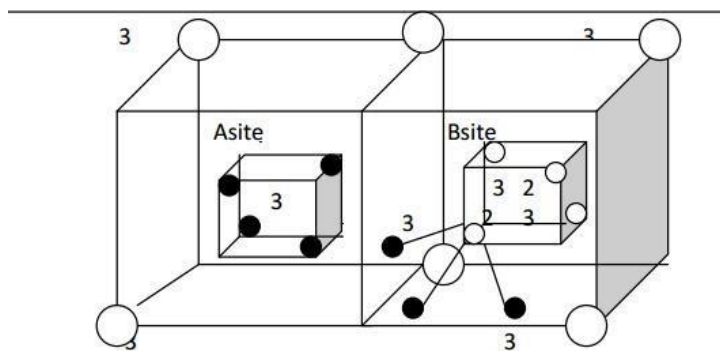
Thus in regular spinel, each divalent metal ion (Mg^{2+}) exists in tetrahedral form (A site) and each trivalent metal ion (Fe^{3+}) exists in an octahedral form (B site). Hence the sites A and B combine together to form a regular spinel ferrite structure as shown in fig (b).



Inverse spinal

In this type, we consider the arrangement of ions of a single ferrous ferrite molecule $\text{Fe}^{3+} [\text{Fe}^{2+} \text{Fe}^{3+}] \text{O}_4^{2-}$. A Fe^{3+} ion (trivalent) occupies all A sites (tetrahedral) and half of the B sites (octahedral) also.

Thus the left out B sites will be occupied by the divalent (Fe^{2+}). The inverse spinal structure is shown in fig (c).



PREPARATION

They have the general chemical composition $\text{A}^{2+} \text{Fe}_2^{3+} \text{O}_4^{2-}$ where A^{2+} represent a divalent metal ion like Zn^{2+} , Mg^{2+} , etc. Ferrites are prepared by sintering a mixture of various metallic oxides as follows.

1. Suitable of A^{2+} and $\text{Fe}_2^{3+} \text{O}_4^{2-}$ in proper proportions are mixed using water or kerosene.
2. The mixing is done in a blender for several hours. It is filtered.
3. The filtered material is dried in a hot oven and is then crushed.
4. Next mixture, is pre-sintered in a furnace at 9000°C to 11000°C for a period of three to fifteen hours, in an air atmosphere or nitrogen atmosphere.

5. The pre-sintered material is then ground into a fine powder and mixed with a binder such as paraffin wax and a solvent such as water.
6. The mixture is then pressed into the desired shapes by using dies.
7. The last step in the process is to place the ferrite in proper vessel in a furnace and heat it to about 1100 to 1400°C. The binder then evaporates. It is cooled in a controlled manner.

PROPERTIES OF FERRITES

Ferrites have net magnetic moment.

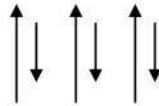
Above Curie temperature, it becomes paramagnetic, while it behaves as ferromagnetic material below Curie temperature.

The susceptibility of ferrite is very large and positive. It is temperature dependent and is given by

$$\chi = C / T \pm \theta \quad \text{for } T > T_N$$

Spin alignment is antiparallel of different magnitudes as shown in fig.

Mechanically it has pure iron character. They have high permeability and resistivity.



They have low eddy current losses and low hysteresis losses.

ADVANTAGES

1. Efficiency is high and cost is low.
2. They have low eddy current losses and low hysteresis losses.
3. Easy to manufacture with great uniformity.
4. They occupy low volume.

Disadvantages

1. The main disadvantage of bubble memory is the requirement of a high recording time for storing and retrieving the data than the charge coupled device (CCD).
2. It requires the interface circuits.
3. When compared with charge coupled device (CCD) memory the magnetic bubble memory has slow access speed.

Applications

They are used to produce ultrasonic waves by magnetostriction principle. Ferrites are used in audio and video transformers.

Ferrite rods are used in radio receivers to increase the sensitivity. They are also used in power limiting and harmonic generation. They are used in computers and data processing circuits.

Ferrites are used in paramagnetic amplifiers so that the input can be amplified with low noise figures.