Electrical Engineering

Electrical Materials

Comprehensive Theory

with Solved Examples and Practice Questions

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Electrical Materials

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CHAPTER 3

Magnetic Properties of Materials

The materials which can be magnetised are called magnetic materials. All materials show some magnetic effect. In many substances the effects are so weak that the materials are often considered to be non-magnetic. However, a vacuum is the only truly non-magnetic medium.

The response of a material at electronic, atomic, molecular and microscopic level to a magnetic field constitutes magnetic properties. Many characteristics of the magnetic materials are similar to the characteristics of the dielectric materials. Atoms and molecules give magnetic dipole moments similar to electric dipole moments. Some magnetic materials exhibit spontaneous magnetization just like spontaneous polarization in dielectrics. The study of magnetic materials can be done parallel to the study of dielectric materials. The difference is that individual electric charges of one sign do exist, whereas, magnetic monopole does not occur. While the electric field is due to fundamental charges, the magnetic field is always associated with an electric current flowing in a loop.

3.1 Parameters

There are three parameters to study the behaviour of magnetic materials:

- Permeability (μ)
- Magnetic dipole moment (p_m)
- Magnetic dipole
- Magnetization (M)

3.1.1 Permeability

Permeability is the ratio of magnetic flux density to the magnetic field intensity present at that material

$$\boxed{\mu = \frac{B}{H}} \qquad \text{...(3.1)}$$

Where, $\mu = \mu_0 \mu_r$

= Permeability

B = Magnetic flux density

H = Magnetic field intensity

Also, $\mu_0 = 4\pi \times 10^{-7}$ H/m

= Permeability of non-magnetic medium (vacuum)

μ_r = Relative permeability

⇒ The factor μ is constant for some materials, but for some materials, the direction in space of vectors $\vec{B}$ and $\vec{H}$ are not the same, in that case μ becomes a tensor.

A quantity expressed as $\chi_m = \mu_r - 1$ is defined as magnetization per unit magnetic field intensity and is called **magnetic susceptibility (χ_m).** This is a dimensionless quantity because magnetization and field intensity have the same units.

NOTE: As $\mu_r \lesseqgtr 1$; so χ_m can have values negative or positive or equal to zero.

3.1.2 Magnetic Dipole

A current loop constitutes a magnetic dipole.

Origin of permanent magnetic dipole in materials

Whenever a charged particle has a angular momentum, particle will contribute to permanent magnetic dipole moment. In general there are three contribution to the angular momentum of an atom.

1. Orbital electron angular momentum → Due to orbital motion of electron.
2. Electron spin angular momentum → Due to self spin of electron.
3. Nucleus spin angular momentum → Due to nucleus spin.

NOTE: Magnetic properties of materials are affected only by electron spin angular momentum.

3.1.3 Magnetic Dipole Moment

The magnetic field produced by a small current loop is similar to the electric field produced from a small electric dipole. For this reason a small current loop is called magnetic dipole. Its dipole moment is defined as equal to the product of the area of the plane loop and the magnitude of circulating current. The vector direction of the dipole moment is perpendicular to the plane of the loop and is along the direction of a right hand screw when moved in the direction of current in the loop

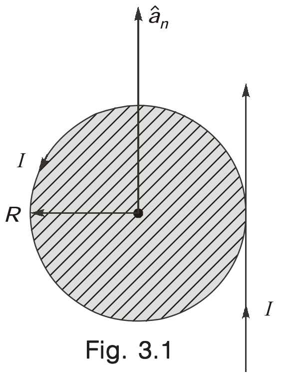


Fig. 3.1

$$\text{Area } \vec{A} = A\hat{a}_n$$

So, dipole moment,

$$\boxed{\vec{p}_m = I A\hat{a}_n} \qquad \text{...(3.2)}$$

Unit of dipole moment is "Ampere/meter^2".

3.1.4 Magnetization

In the presence of magnetic field all materials acquire magnetic dipole moments. The magnitude of dipole moment per unit volume, is called the **magnetization** of the medium (material) and is described by a vector $\vec{M}$ A/m. When a magnetic field is applied to a material, the magnetic induction (flux density) is the sum of the effect on vacuum and that on the material, so that,

$$\vec{B} = \mu_0\vec{H} + \mu_0\vec{M} \qquad \text{...(3.3)}$$

$$= \mu_r\vec{H}$$

3.7 Antiferromagnetic Material

These are the materials which have antiparallel alignment of magnetic dipoles because of very small distance between interacting atoms. The net magnetization of these materials is zero even in the presence of magnetic field.

$$M = 0$$

$$M = \chi_m H = 0$$

$$\Rightarrow \qquad \chi_m = 0$$

As $\qquad \mu_r = 1 + \chi_m$

So, $\qquad \boxed{\mu_r = 1}$

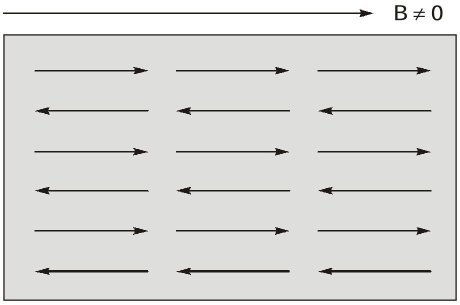


Fig. 3.18

The antiferromagnetic material loses its property and starts behaving like paramagnetic material above a critical temperature known as **Neel's temperature.**

Below Neel's temperature, these materials have increasing susceptibility with increase in temperature. Above Neel's temperature these materials follow:

$$\boxed{\chi_m = \frac{C}{T + \theta}}; \quad T > T_N$$

The most important feature of antiferromagnetic material is the occurrence of a very sharp maxima in the susceptibility Vs temperature curve. The temperature at which this maxima occurs is known as Neel's temperature (T_N).

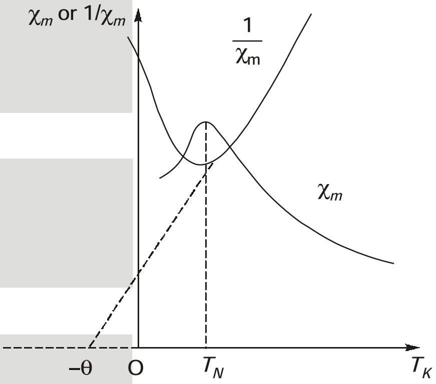


Fig. 3.19 : *Susceptibility as a function of temperature for an antiferromagnetic material*

Many substances have been discovered which shows the antiferromagnetic behaviour and most of them are ionic compounds (like oxides, sulphides and chlorides etc).

E.g. MnO, MnS, Cr_2O_3, NiCr, MnF_2.

3.8 Ferrimagnetic Materials

In ferrimagnetic materials magnetic dipoles are aligned in antiparallel direction but strength of dipole moment is higher in one direction as compared to other direction, so as a result material possess net magnetization. The ferrimagnetic materials with low conductivity and high resistivity are known as **ferrites.**

Ferrites losses their property of ferrimagnetism above a critical temperature known as Curie-temperature and starts behaving like paramagnetic material. Below Curie temperature they exhibit similar property as that of ferromagnetic materials (Property of hysteresis). Ferrites have high resistivity so they are preferred for high frequency applications (upto microwave frequencies).

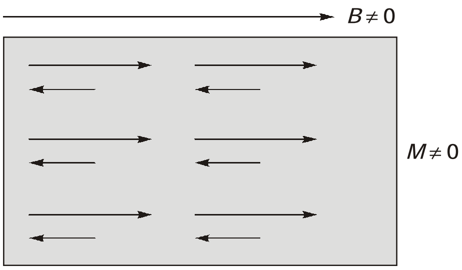


Fig. 3.20

Example 3.9 Which one of the following is the correct statement?

YIG and YAG are two types of crystals used extensively in technology and are

(a) non-magnetic and magnetic, respectively
(b) magnetic and non-magnetic, respectively
(c) both magnetic
(d) both non-magnetic [IES-2007]

Ans. (b)

In YIG, I represent Iron i.e. (Yttrium Iron Garnet).

In YAG, A represent Aluminium i.e. (Yttrium Aluminium Garnet).

Example 3.10 Match List-I (Material) with List-II (Properties) and select the correct answer using the code given below the lists:

List-I	List-II
A. Superconductor	1. Susceptibility +ve at very low temperatures
B. Ferric chloride	2. Very small –ve susceptibility
C. Diamond	3. Very high –ve susceptibility
D. Manganese oxide	4. Susceptibility inversely proportional to $(T + \theta)$

Codes:

	A	B	C	D
(a)	2	4	3	1
(b)	3	1	2	4
(c)	2	1	3	4
(d)	3	4	2	1

[IES-2007]

Ans. (c)

Super conductor is diamagnetic so very small (–ve) susceptibility. Ferric chloride is paramagnetic so susceptibility +ve. MnO is Antiferromagnetic so follow Curie Weiss law after Neel temperature.

Example 3.11 Ferromagnetic materials show hysteresis in B–H characteristic. As the magnetic field is increased slowly from zero value, what is the first process which sets in the material to give net magnetization?

(a) Growth of favourably oriented domains at the cost of other domains by reversible boundary displacements
(b) Growth of favourably oriented domains at the cost of other domains by irreversible boundary displacements
(c) Domain wall orientation
(d) A combination of processes (a) and (c) above

[IES-2009]

Ans. (d)

Do You Know ?

- A **"Vaccum"** is the only truly non-magnetic medium.
- Hard magnetic materials are used for making permanent magnets.
- Soft magnetic materials are used for large scale generators, transformers, inductors, motors etc.
- **Nucleus MRI** is based on the **spin of the nucleus.**
- **Metallic Bismuth (Bi)** has the **greatest diamagnetic character.**
- Materials used in transformer should have low **hysteresis loss** and **high permeability.**
- **Molecular field** $(\lambda\vec{M})$ is mainly responsible for alignment of dipoles in one direction.
- Spontaneous magnetization (M_r) is given by

$$\boxed{M_r = \frac{B_r}{\mu_0}}$$

- Resistivity of ferrites are more than that of ferrimagnetic materials.
- **Barium ferrites** are the most important type of ceramic permanent magnetic materials.
- **Barrium ferrites** ($BaO.6\ Fe_2O_3$) are used as **focusing magnets for TV tubes** and in small **DC motors** and in **compact torque drives.**
- **YIG (yttrium-iron-garnet)** are found to use in magnetic bubble memory and assorted microwave devices.
- When **Silicon** is mixed with **Iron** then it,
  - ⇒ increases the permeability.
  - ⇒ reduces the hysteresis loss.
  - ⇒ increases the resistivity.
  - ⇒ also increase the life of materials.
- The magnetic permeability is related to magnetostriction, and for high permeability materials application an effort is made to keep magnetostriction as low as possible.

Student's Assignments 1

1. Obtain the relation between μ_r, χ_m, M and H.

2. State the laws for susceptibilities of Para, Dia, Ferro-, Ferri- and Antiferro type magnetism involving temperature dependence.

3. A paramagnetic system of electronic spins is subjected to H-field = 10^6 A/m at 300 K. Find the average magnetic moment along H direction per spin in Bohr magneton. What is its value at 4.2 K?

4. What sort of magnetic properties are desirable for the core material for transformer action listed below?
   (a) 60 Hz power transformer (b) AF power transformer
   (c) RF power transformer (d) Pulse transformer (supermalloy)
   (e) Microwave action (f) Magnetic shielding action

5. Explain the phenomena of magnetostriction.

Student's Assignments 1 Explanation

Solution: 1

The magnetic flux B induced in a magnetic material subjected to external magnetic field H, is given by $B = \mu H$, where μ = magnetic permeability.

$$\text{Actually } B = \mu_0(H + M) = \mu H$$

μ_0 = permeability of free space, where M = magnetism acquired = density of magnetic moment.

Since the magnetisation ∝ applied field H, the factor of proportionality is called susceptibility χ.

$$\therefore \qquad \chi_m = \frac{M}{H} \text{ and } B = \mu_0(H + M)$$

$$\mu = \frac{B}{H} = \mu_0\left(\frac{H}{H} + \frac{M}{H}\right) = \mu_0(1 + \chi_m)$$

$$\therefore \qquad \left.\begin{aligned} \mu &= \mu_0(x + \chi_m) \\ \frac{\mu}{\mu_0} &= \mu_r = \frac{\mu_0}{\mu_0}(1 + \chi_m) \end{aligned}\right\} \mu_r = 1 + \chi_m$$

where μ_r = relative magnetic permeability with respect to μ_0.
χ_m = magnetic susceptibility
μ = magnetic permeability and
$\chi_m = \mu_r - 1$

Solution: 2

(a) Diamagnetism

$$\chi_d = \frac{\mu_0 N Z e^2 r^2}{6\text{m}}; N = 10^{29}/\mu^3, Z = 10, r^2 = 10^{-20}\text{ m}^2$$

where e = electronics charge
m = electronics mass

$$\chi_d = 10^{-5} \text{ very very weak}$$

(b) Paramagnetism

$$\chi_m = \frac{M}{H} = \frac{\mu_0 N P_m^2}{3kT} = \frac{C}{T}$$

$$\chi_m = \text{susceptibility} = \frac{M}{H}$$

where M = resultant magnetic moment and its density
H = applied magnetic field used for magnetization of the material
μ_0 = permeability of free space
N = magnetic dipole moment P_m per atom in unit volume
k = Boltzmann constant
T = absolute temperature K

CHAPTER 4

Conductive Materials

The conductivity of solids spans a wide range of values to about twenty-three orders of magnitude. No other quantity varies to such an extent. In the present chapter, we will discuss conductive materials which have high conductivity. The main facts relating to conductivities of metals explained are: the range and variation, the temperature dependence, the pressure dependence, the relation of thermal conductivity to electrical conductivity, the conductivity of impure metals or dilute alloys. The properties and applications of high and low conductive materials, and the physics and applications of superconductors have also been discussed.

4.1 Electrical Conductivity

As we know that a basic property of a material is its resistivity. Resistivity of a material is related to its resistance as follows:

$$R = \rho \frac{l}{A}$$

where, R = Resistance, ρ = Resistivity, l = Length and A = Area

Resistivity (ρ) is expressed in **ohm-m.**

Electrical conductivity (σ) is the reciprocal of electrical resistivity and is expressed in **ohm^{-1} m^{-1}.**

At room temperature a typical insulator has conductivity in the range of 10^{-16} ohm^{-1} m^{-1}, whereas for a semiconductor the value might be 10^{-2} ohm^{-1} m^{-1}, and for a metal such as silver, the conductivity will be as high as 10^{8} ohm^{-1} m^{-1}.

High conductivity of metals is due to the presence of **free or conduction electrons.** These electrons are able to move freely in the lattice and do not belong to any particular atom. These free electrons are given the name of electron gas.

4.2 Free Electron Theory of Metals-Ohm's Law

Temperature is the major contributing factor to determine the random velocities of electrons in a particular direction in the absence of electric field. Although the net drift velocity is zero.

On application of electric field, the electrons acquire a systematic velocity, so that, the motion of electrons will have two components:

(i) random motion depending upon temperature,

(ii) directed motion determined by electric field polarity.

Consider a system of free electrons in a conductor which is subjected to an electric field, E volt/m, figure (4.1). Let, at any moment average forward acceleration of the electron be $\frac{d^2x}{dt^2}$ in the x direction due to the field with m as the mass of the electron and $-e$ as the charge, we have

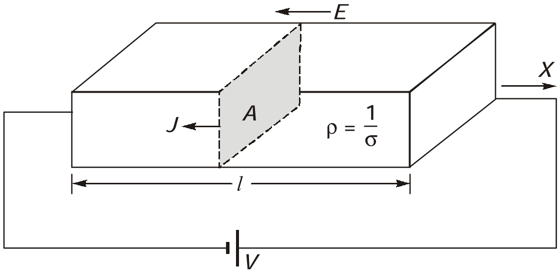


Fig. 4.1: *Conductor with electric field E*

$$m\frac{d^2x}{dt^2} = -eE \qquad \text{...(4.1)}$$

where E is the force acting on a unit electron charge.

Integrating equation (4.1), we have

$$m\frac{dx}{dt} = -eEt + A$$

(A is a constant)

or
$$\frac{dx}{dt} = -\frac{e}{m}Et + C \qquad \text{...(4.2)}$$

where C is a constant.

$\frac{dx}{dt}$ represents a velocity. Obviously C must have dimensions of velocity, and can only be random velocity of the electrons. So,

or
$$\frac{dx}{dt} = -\frac{eE}{m}t + v_{\text{random}} \qquad \text{...(4.3)}$$

v_{random} averages to zero, as there is no net transfer of charge in the absence of the field. Taking average effect of (4.3), we have

$$\frac{dx}{dt} = v_x = -\frac{eE\tau}{m} \qquad \text{...(4.4)}$$

where v_x is average drift velocity, and τ is called the collision time, average interval of successive collisions between the electrons and the lattice (ion cores).

Let I_x be the current carried along the conductor of cross-section A, in say x direction by electrons of charge $-e$ and drift velocity v_x. With 'n' as the electrons per unit volume, the charge flowing through the section in time dt,

$$dq = -e\,n\,Av_x dt$$

$$\frac{dq}{dt} = I_x = -e\,n\,Av_x$$

and
$$J_x = \frac{I_x}{A} = -env_x \qquad \text{...(4.5)}$$

where J_x is current density. From equation (4.4) and (4.5) we have,

$$J_x = \frac{ne^2\tau}{m}E \qquad \text{...(4.6)}$$

Here,
$$\sigma = \frac{ne^2\tau}{m} \qquad \text{...(4.7)}$$

4.10 Application of Conducting Materials

- In transmission lines and cables.
- In DC machines.
- In synchronous generators.
- In transformers.
- In 3-phase induction motors.

4.11 Conductors for Electrical Machines

The fundamental requirements to be met by high conductivity materials to be used for electrical machines are:

- highest possible conductivity.
- rollability and drawability.
- good weld ability and solderability.
- least possible temperature coefficient.
- adequate mechanical strength.
- adequate resistance to corrosion.

4.12 Thermal Conductivity of Metals-Wiedemann Franz Law

All solids conduct heat. In general, the best heat conductors are the metals. Among the metals the best electrical conductors are also the best heat conductors. In such conductors just like electrical conductivity, the heat conduction is mostly through valence (free) electrons.

When two bodies at different temperatures are brought in contact with each other, heat Q flows from hotter to the colder substance. The change in energy, ΔE, of a system can be expressed by the first law of thermodynamics

$$\Delta E = W + Q \qquad (4.21)$$

where, W is the work done to the system and Q is the heat received by the system from the environment. If W is considered to be zero then

$$\Delta E = Q \qquad ...(4.22)$$

Energy, work and heat have the same unit of Joule (J).

Different substances need different amount of heat to raise their temperature by some units i.e. degrees. The **heat capacity** C is the amount of heat dQ which is needed to be transferred to a substance in order to raise its temperature by a certain temperature level, having the unit J/K or J/°C. The heat capacity at constant volume is defined as

$$C_v = \left(\frac{\partial E}{\partial T}\right)_v \qquad ...(4.23)$$

The specific heat capacity, c is the heat capacity per unit mass

$$c = \frac{C}{m} \qquad ...(4.24)$$

The thermal energy which is transferred to a system equals the product of mass, increase in temperature, and specific heat capacity

$$\Delta E = Q = m\Delta T\, c_v \quad (c = c_v) \qquad ...(4.25)$$

Consider a rectangular bar of unit cross-section as shown in figure (4.3). A temperature gradient is maintained along this bar with temperature T_1 at one end of the bar and T_2 at the other end.

If $T_1 > T_2$, then heat flows down the bar in the negative x direction.

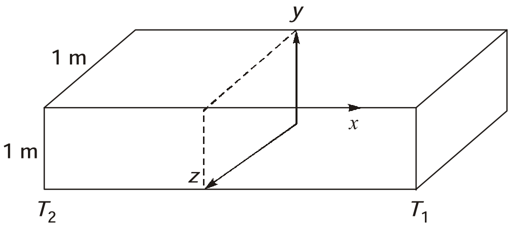


Fig. 4.3: *Heat flow in a bar* $T_1 > T_2$

CHAPTER

5

Semiconductor Materials

Most of the semiconductors are crystalline in nature and these are broadly divided into elements (**ex.: Silicon** and **Germanium**) and compounds **(ex.: GaAs, InP, GaP etc.).** All semiconductor materials (elemental or compounded) have number of common attributes:

- Electrical resistivity is lying between **10^{-5} to about 10^{7} Ω-m.**
- Conductivity of semiconductors increases in bright surroundings (optical effects).
- Semiconductor become better conductors as the temperature is raised.
- Like dielectrics, semiconductors can support internal electrical fields.
- Single crystal materials are required for majority of devices.
- These materials are generally hard and brittle.
- Current in semiconductors does not obey **Ohm's Law** and will increase rapidly than voltage, i.e. **semiconductors are non-linear devices.**

5.1 Electrical Conductivity of Metals, Semiconductors and Insulators

The main difference in conductivity of conductors, semiconductors and insulators is due to the peculiarities of their internal structure and concept of energy bands in solid. The **width of the forbidden band** determines the characteristics of a material as insulator, semiconductor or conductor because that decides the amount of energy required for an electron in valence band (V.B) to cross over the gap to conduction band (C.B) by the application of an external electric field or by thermal energy.

In semiconductor, the E_G **(gap energy)** is of the order of **1** *eV*. The Valence Band (V.B) is filled and electrons can not move over to C.B, However when the temperature is raised (say at room temperature) some valence electrons acquire enough or more thermal energy to overcome the forbidden gap energy and cross-over to the conduction band. In the case of a conductor there is no forbidden gap between valence band and conduction band, hence the valence band and conduction bands overlap.

Different materials like insulators, semiconductors and metals have different energy band structures as shown below:

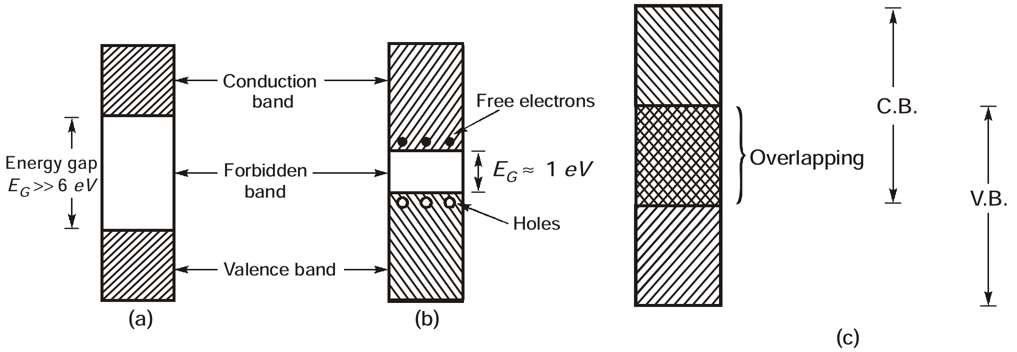
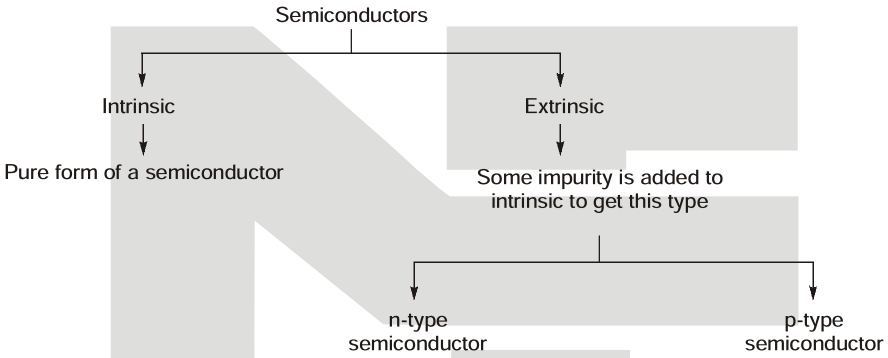


Fig. 5.1: *(a) An insulator (diamond), (b) A semiconductor (graphite, germanium, silicon) (c) A metal (aluminium, copper)*



Some points should be noted here

- In intrinsic semiconductor, total number of free electrons is equal to the total number of holes.
- N-type or Donor type impurity are pentavalent atoms such as *P*, *As*, *Sb*, *Bi* etc.
- P-type or Acceptor type impurity are trivalent atoms such as *B*, *Al*, *Ga*, *In*, *Th* etc.

5.2 Electrons and Holes in an Intrinsic Semiconductor (Pure Semiconductor)

Consider a crystal structure of *Ge* at 0°K in figure 5.2 and at room temperature in figure (5.3).

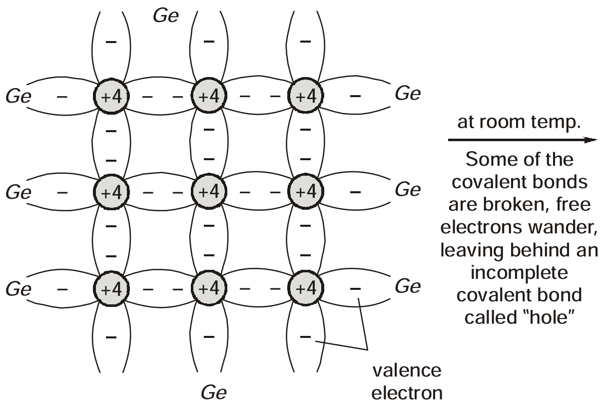


Fig. 5.2

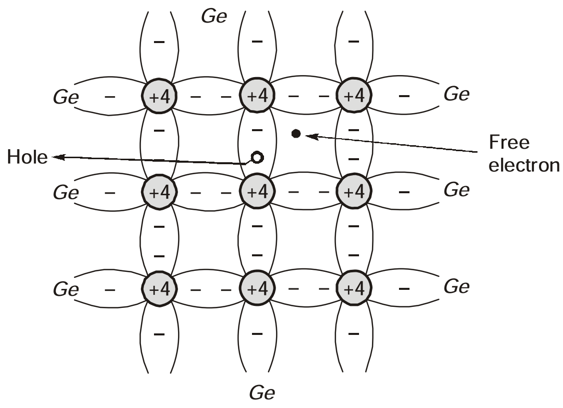


Fig. 5.3