

PHYSICS OF SOLIDS

LEARNING OBJECTIVES

At the end of this chapter the students will be able to:

Distinguish between the structure of crystalline, glassy, amorphous and polymeric solids.

Understand the idea of lattice.

Appreciate that deformation is caused by a force and that, in one dimension, the deformation can be tensile or compressive.

Define and use the terms Young's modulus, bulk modulus and shear modulus.

Describe an experiment to determine elastic limit and yield strength.

Distinguish between elastic and plastic deformation of a material.

Synthesize and deduce the strain energy in a deformed material from the area under the force extension graph.

Describe the energy bands in solids.

Classify insulators, conductors, semi-conductors on the basis of energy bands.

Distinguish between intrinsic and extrinsic semiconductors.

Explain how electrons and holes flow across a junction.

Describe superconductors.

Distinguish between dia, para and ferro magnetic materials.

Understand and describe the concept of magnetic domains in a material.

Know the Curie point.

Classify hard and soft ferro magnetic substances.

Understand hysteresis and hysteresis loss.

Solids are the substances which maintain their volume and shape under normal conditions. The specific uses of solids such as conducting property of Cu, the hardness of steel, the magnetic character of iron and softness of lead depend upon the structure of these solids.

Q.1 Explain the classification of solids.

Ans. CLASSIFICATION OF SOLIDS

Solids consist of the following types

- (1) Crystalline Solids
- (2) Amorphous or Glassy Solids
- (3) Polymeric Solids

(1) Crystalline Solids

Crystalline solids are those solids in which their atoms / molecules are arranged in particular fashion. This arrangement of atoms / molecules is repeated in the solid in 3-dimensions.

Examples of Crystalline Solids

Metals like Cu, Fe, Zn and some compounds like sodium chloride and ceramics like zirconia are crystalline solids. The crystal structure is usually studied by diffraction of x-rays from crystals.

Movement of Atoms / Molecules and Effect of Temperature

Atoms / molecules in crystalline structure continuously vibrate about their mean positions with certain amplitudes. The amplitude of vibration increases with rise of temperature of solid. The cohesive force (force of attraction between two molecules of same substance) between atoms / molecules hold them in particular order in long distance inspite of their rapid vibrations.

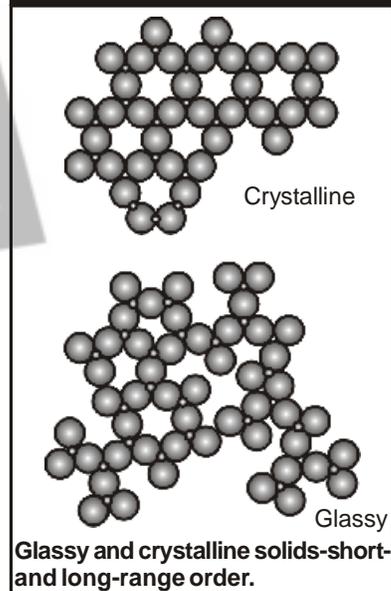
Melting Point of Solid

For every solid, there is particular temperature at which the vibrations of the atoms / molecules of solid becomes so great that the structure of the solid suddenly breaks and the solid melts. This temperature at which the solid changes into liquid is called melting point of the solid. Every crystalline solid has a definite melting point.

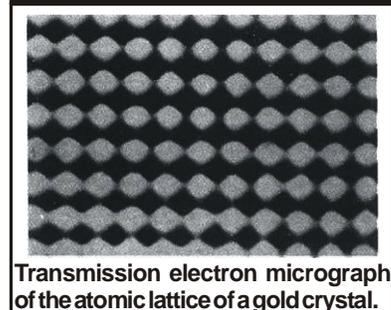
(2) Amorphous or Glassy Solids

The solid which has no particular arrangement of their atoms / molecules is called amorphous or glassy solid. As there is no regular arrangement of atoms, therefore amorphous solids are more like liquids

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with the disordered structure frozen in.

Example

Glass which is solid at ordinary temperature has no regular arrangement of molecules. On heating, it softens into paste like state before it becomes very viscous liquid at almost 800°C . Thus amorphous solids are called glassy solids. This type of solids have no definite melting point.

(3) Polymeric Solids

Polymeric solids are more or less solid materials with a structure between order (solid) and disorder (liquid). They can be classified as partially or poorly crystalline solids.

Example

Natural polymeric solid is rubber which is in pure state composed of hydrocarbon with the formula $(\text{C}_5\text{H}_8)_n$.

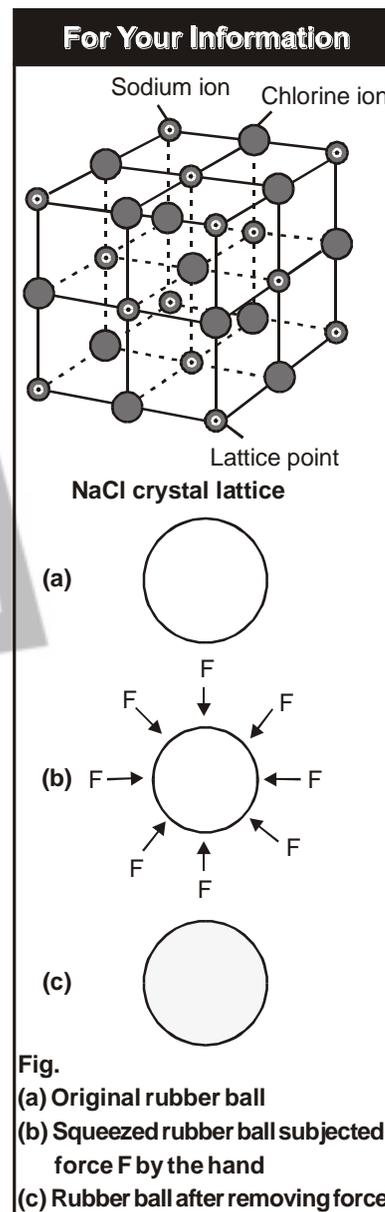
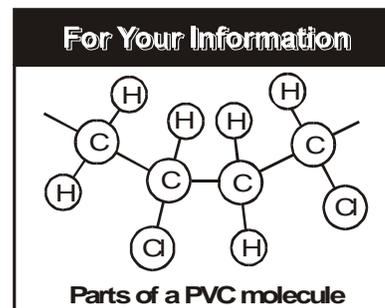
Plastic and synthetic rubbers are polymers because they are formed by polymerization reaction in which relatively simple molecules are chemically combined into massive long chain molecules or “*three dimensional structure*”. These materials have low specific gravity compared with even the highest of metals and yet exhibit good strength to weight ratio. Polymers consist wholly or in part of chemical combinations of carbon with oxygen, H_2 , N_2 and other metallic or non-metallic elements. Polythene, polystyrene and nylon etc. are examples of polymers.

(4) Crystal Lattice

The smallest three dimensional part of crystal which consists of structures of arrangement of atoms is called unit cell. The whole structure obtained by repetition of unit cell is known as crystal lattice.

Example

The pattern of NaCl particles have a cube shape. In cube crystal shapes have corners in which one or more of the angles are not right angles.



Q.2 What are the mechanical properties of solids?

Ans. MECHANICAL PROPERTIES OF SOLIDS

Deformation in Solids

If a soft rubber ball is pressed in hands or a rubber string is stretched, the volume of the ball decreases and length of string increases. The change in volume and length on application of force is called deformation.

On removing the force, the ball and rubber string come to the initial state.

Similarly in crystalline solids, the atoms are arranged in regular fashion and they are held under inter-atomic cohesive force. When external force is applied on such a solid, a deformation occurs because of displacement of atoms from their mean position. After removal of external force, the atoms return to their mean positions.

Elasticity

It is the property of matter by which it regains its original position as soon as the deforming force is removed.

Figure shows deformation produced in unit cell of a crystal subjected to an external applied force. The results of mechanical tests are usually expressed in terms of stress and strain, which are defined in terms of applied force and deformation.

Stress

It is defined as the force applied on unit area to produce any change in shape, volume and length of a body. Mathematically if F is the force applied on area A , then stress can be expressed as

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

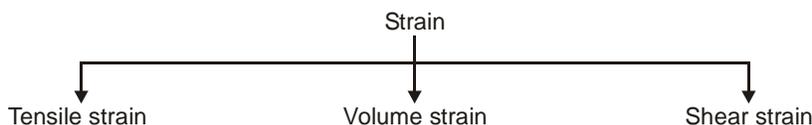
$$\sigma = \frac{F}{A}$$

Unit of σ (stress) is Nm^{-2} or pascal (Pa).

When a stress changes length, it is called the tensile stress, when it changes the volume it is called the compressional or volumetric stress and when it changes the shape it is called the shear stress.

Strain

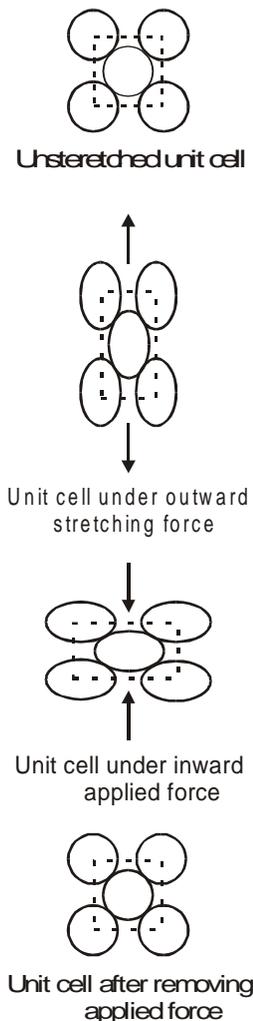
It is defined as the fractional change in length, volume or shape on application of stress. Strain is of three types



Tensile Strain

It is defined as the fractional change in length on applying stress.

If Δl is the change in length and l is the original length, then tensile strain is given by



$$\text{Tensile strain} = \frac{\text{Change in length}}{\text{Original length}}$$

$$\varepsilon = \frac{\Delta l}{l}$$

Strain has no units.

Volumetric Strain

It is defined as the fractional change in volume on applying stress.

If ΔV is the change in volume and V is the original volume, volume strain is given by

$$\text{Volume strain} = \frac{\text{Change in volume}}{\text{Original volume}}$$

$$\text{Volume strain} = \frac{\Delta V}{V}$$

Shear Strain

Consider a rigid cube whose opposite faces are subjected to shear stress, the shearing strain produced is given by

$$\gamma = \frac{\Delta a}{a} = \tan \theta$$

If ' θ ' is very small, then $\tan \theta \simeq \theta$

$\therefore \gamma = \theta$ ' θ ' is measured in radian.

Elastic Constant

Elastic constant is defined as, with in elastic limit the ratio of stress to strain is a constant named as elastic constant. There are three elastic constants:

- (i) Young's Modulus
- (ii) Bulk Modulus
- (iii) Shear Modulus

(i) Young's Modulus

It is defined as ratio of stress to tensile strain. Mathematically

$$\text{Young's Modulus} = \frac{\text{Stress}}{\text{Tensile strain}}$$

$$\text{But Stress} = \frac{F}{A}$$

$$\text{and Tensile strain} = \frac{\Delta l}{l}$$

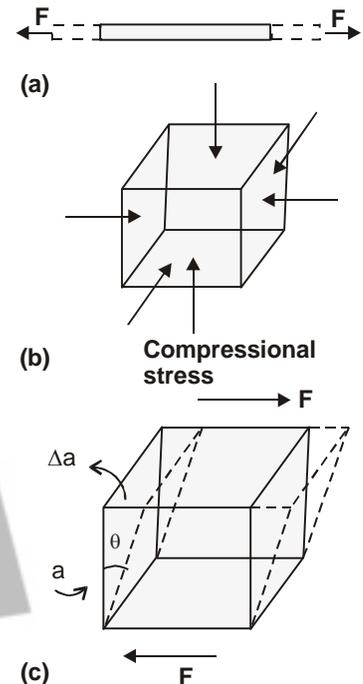


Fig.

(a) Wire pulled along its length by stretching force F .

(b) Cylinder subjected to compressive force F .

(c) Cube subjected to shearing force F .

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Forces and their effects
 systems and their properties
 against the forces and
 the static equilibrium

So

$$Y = \frac{F/A}{\Delta l/l} = \frac{Fl}{A\Delta l}$$

The unit of Y is Nm^{-2} (Pa).

(ii) **Bulk Modulus**

The ratio of stress to volume strain is called Bulk Modulus. Mathematically

$$\text{Bulk Modulus} = \frac{\text{Stress}}{\text{Volumetric strain}}$$

Cubic system



Triclinic system



Tetragonal system



Hexagonal system



Trigonal system



Rhombic system



Monoclinic system



$$K = \frac{F/A}{\Delta V/V} = \frac{FV}{A\Delta V}$$

$$K = \frac{FV}{A\Delta V}$$

The unit of K is Nm^{-2} (Pa).

(iii) Shear Modulus

It is defined as the ratio of stress to shearing strain.

Mathematically

$$\text{Shearing modulus} = \frac{\text{Stress}}{\text{Shear strain}}$$

$$G = \frac{F/A}{\tan \theta}$$

The unit of G is Nm^{-2} (Pa).

TABLE OF ELASTIC CONSTANT

Material	Young's Modulus 10^3 Nm^{-2}	Bulk Modulus 10^9 Nm^{-2}	Shear Modulus 10^9 Nm^{-2}
Aluminium	70	70	30
Bone	15	–	80
Brass	91	61	36
Concrete	25	–	–
Copper	110	140	44
Diamond	1120	540	450
Glass	55	31	23
Ice	14	8	3
Lead	15	7.7	5.6
Mercury	0	27	0
Steel	200	160	84
Tungsten	390	200	150
Water	0	2.2	0

Q.3 Explain elastic limit and yield strength with the help of graph.

Ans. ELASTIC LIMIT AND YIELD STRENGTH

In tensile test, metal wire is subjected to a stress and deformations are continuously measured by a suitable electronic device fitted in the mechanical testing machine and typical stress-strain graph for a ductile material is shown in figure.

Explanation from Graph

From O to A

In the initial stage of deformation, stress is increased linearly with the strain till point 'A' is reached. This is called proportional limit (σ_p).

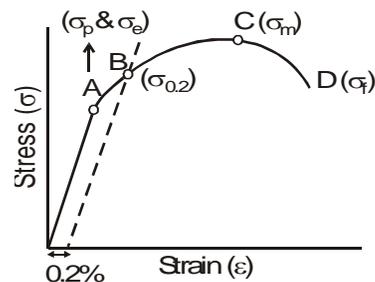
It is defined as the greatest stress that a material can endure without losing straight line proportionality.

Note: For all practical purposes, the proportional limit can be regarded as identical with elastic limit (σ_e).

It is defined as the greatest stress that a material can endure without any permanent change in shape or dimension.

Hooke's Law

Hooke's law (which states that stress is directly proportional to strain) is obeyed in the region OA. Deformation produced in the material from O to A is temporary as the material can regain its original shape or dimensions on removing the applied stress. Such a temporary deformation is known as elastic deformation.



From A to B

If the stress is increased beyond 'A', to B the graph loses straight line but still specimen regain its shape when applied force is removed. The stress at point B is elastic limit and point B is called yield point beyond the yield stress or elastic limit of the material, the specimen becomes permanently changed and does not recover its original shape or dimension after the stress is removed. This kind of behaviour is called plasticity.

At Point C

Point C represents the ultimate tensile strength (UTS) σ_m of the material.

It is defined as the maximum stress that a material can withstand, and can be regarded as nominal strength of the material.

Once the point C is reached corresponding to UTS and stress is further increased, the material breaks at point D. The stress corresponding to point D is called fracture stress (σ_f).

Ductile Substances

Substances which undergo plastic deformation until they break, are known as *ductile substance*. e.g., Lead, iron and wrought iron are ductile substances.

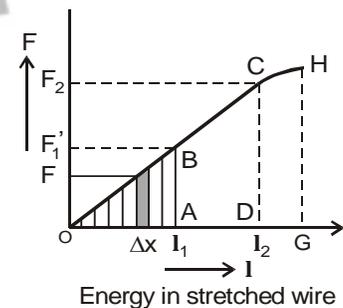
Brittle Substances

Those substances which break just after elastic limit is reached are known as brittle substances. e.g., Glass and high carbon steel are brittle substances.

Q.4 What is meant by strain energy? Derive the relation for strain energy in deformed material from the area under the force extensions graph?

Ans. STRAIN ENERGY IN DEFORMED MATERIALS

Consider a wire suspended vertically from one end. It is stretched by attaching a weight on the other end. The stretching force is gradually increased and corresponding extension produced in wire is calculated. If elastic limit is not crossed, the graph drawn between force and extension is straight line. As force F_1 stretched the wire, so it does work on the wire which is stored as PE in wire. The work done by F_1 force in stretching the wire does not remain constant in producing extension l_1 , it varies uniformly from O to F_1 . In such a situation work is calculated by graphical method.



Let at any instant, the applied force is F before the extension l_1 is reached and the wire extends by Δx . The extension Δx is so small that practically the force F may be assumed as constant. So work done in producing small extension Δx is $F \Delta x$. In figure it can be seen that it represents by the area of the shaded strip. In this way the total extension l_1 can be divided into very small extensions and the work done during each of these small extensions would be given by area of the strips. So total work done in producing extension l_1 is the sum of area of all these strips which is equal to the area between graph and x-axis upto l_1 . In this case it is equal to area of triangle OAB.

$$\begin{aligned} \text{Work done} &= \text{Area of } \triangle OAB \\ &= \frac{1}{2} \times OA \times AB \end{aligned}$$

$$\text{Work done} = \frac{1}{2} l_1 \times F_1 \quad \dots\dots (i)$$

This is the amount of energy stored in the wire. It is the gain in PE of the molecules due to their displacements from their mean positions.

Eq. (i) can be expressed in terms of modulus E . If A is the area of cross-section of wire and L is the original length of wire, then

$$E = \frac{F_1/A}{l_1/L} = \frac{F_1 L}{A l_1}$$

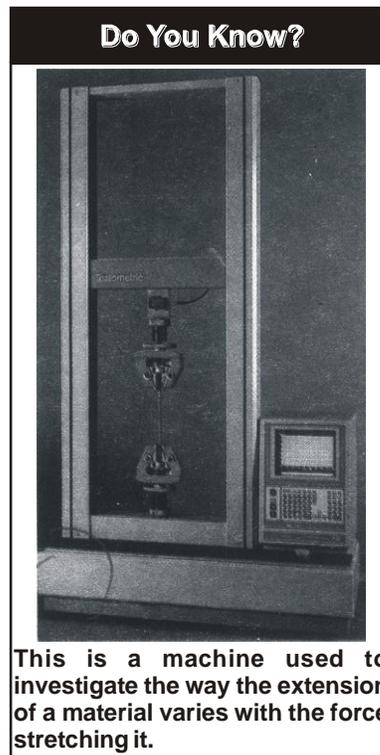
or $F_1 = \frac{EA l_1}{L}$

Putting F_1 in (i), we have

$$\text{Work done} = \frac{1}{2} l_1 \frac{EA l_1}{L}$$

$$\text{Work done} = \frac{1}{2} \left[\frac{EA \times l_1^2}{L} \right]$$

The area method is quite a general one. If extension is increased from l_1 to l_2 , the work done by stretching force would be given by the area of trapezium ABCD. It is also valid for both linear and non-linear parts of force-extension graph. If extension occurs from O to G, this work done would be area of OHG.



Q.5 What are the electrical properties of solids?

Ans. ELECTRICAL PROPERTIES OF SOLIDS

The fundamental electrical property of a solid is its ability to conduct electric current. The electrical behaviour of different solids is different. The solids are classified into three groups regarding their electrical behaviour.

(1) Conductors

The solids which conduct electricity through them are called conductors. e.g., Metals are conductors having conductivity of the order of $10^7 (\Omega \text{ m})^{-1}$.

(2) Insulators

The solids which do not conduct electricity through them are called insulator. e.g., Wood, diamond etc. have conductivity ranging between 10^{-10} and $10^{-20} (\Omega \text{ m})^{-1}$.

(3) Semi-conductor

Those solids which have conductivity between conductors and insulators are called semi-conductors. e.g., Silicon and Germanium which have conductivity ranging from 10^{-6} to $10^{-4} (\Omega \text{ m})^{-1}$.

The free electric theory based on Bohr Model of electron distribution in an atom failed to explain completely the different electrical behaviour of solids. The energy band theory based on wave mechanical model of an atom explained successfully the electrical behaviour of solids.

Q.6 What is energy band theory?

Ans. ENERGY BAND THEORY

Electrons of an isolated atom are bounded to the nucleus and can have energy levels which are distinct. However when a large number of atoms say N , are brought close to one another to form a solid, each energy level of the isolated atom splits into N -sublevels, called states, under the action of the forces exerted by other atoms in the solid. These permissible energy states are discrete but so closely spaced that they appear to form a continuous energy bands. In between two permissible energy bands, there is range of energy states which cannot be occupied by electrons. These are called forbidden energy states and its range is said to be forbidden energy gap.

Valence Energy Band

The electrons revolving in outermost orbit are called valence electrons. The energy band occupied by valence electrons is called “valence energy band”. It is highest occupied energy band in an atom. This cannot be empty. It is either partially filled or completely filled.

Conduction Energy Band

The permissible energy band which is next above the valence band is called conduction band. This band may be occupied by free electrons, which can conduct electric current through solid. The electrons corresponding to this energy band are called conductive electrons or free electrons. Any electron escaping from valence band may be accommodated by this band. The conduction band may either be empty or it may be partially filled.

Filled Energy Band

The energy band below valence energy band called filled energy bands, these are stable bands and electrons of these bands play no part in the conduction of current through solid.

Q.7 Explain conductors, insulators and semi-conductors on the basis of energy band theory.

Ans. CLASSIFICATION OF CONDUCTORS, INSULATORS AND SEMI-CONDUCTORS ON THE BASIS OF ENERGY BAND THEORY

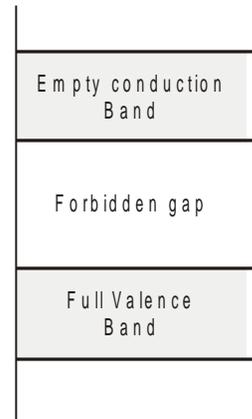
Do You Know?

Gas is also known as solid
liquid case is not a solid
in regular arrangement
but in random positions

Insulators

Insulators are those solids in which valence electrons are bound very tightly to their atoms and are not free. In terms of energy bands, it means that an insulator as shown in figure has

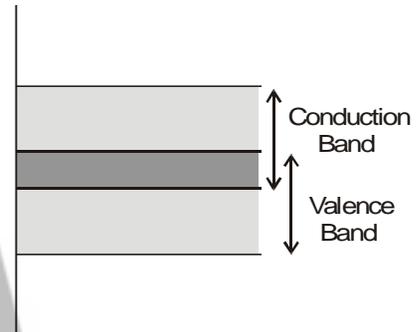
- An empty conduction band (i.e., no free electron).
- A full valence band,
- A large energy gap between them.



Conductors

Conductor are those solids which have plenty of free electrons for electrical conduction. In terms of energy bands, it means that conductors are those materials in which valence and conduction bands largely overlap each other as shown in figure. There is no physical distinction between the two bands which ensures the availability of large number of free electrons. Thus, conductors have

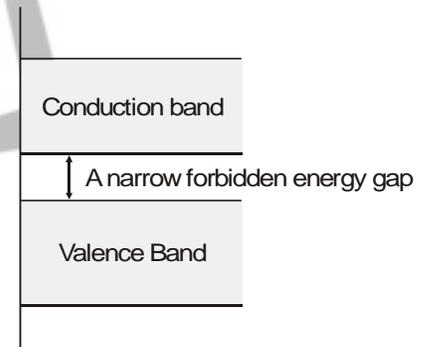
- Filled conduction band.
- Filled valence energy band.
- Overlapping of conduction and valence energy band.



Semiconductors

Semiconductors at room temperature have the following properties

- Partially filled conduction band.
- Partially filled valence band.
- Very narrow forbidden energy gap (1 eV) between valence and conduction energy bands.



At 0 K, there are no electrons in the conduction band and their valence band is completely filled. It means at 0 K, a piece of Ge or Si is a perfect insulator. However, with increase in temperature, some electrons possess sufficient energy to jump across the small energy gap from valence to conduction band. This transfers some free electrons in the conduction bands and creates some vacancies of electrons in the valence band. The vacancy of electron in the valence band is known as a hole. It behaves like a positive charge. Thus at room temperature, Ge or Si crystal becomes a semiconductor.

Intrinsic and Extrinsic Semiconductors

Intrinsic Semiconductors

A semiconductor in its extremely pure form is known as intrinsic semiconductor. The electrical behaviour of semiconductor is very sensitive to the purity of material and changes suddenly on introducing a small amount of impurity into pure semiconductor lattice.

Q.8 *What is doping? Describe the formation of n-type and p-type semi-conductors.*

Ans. **DOPING**

The process of mixing controlled amount of impurity of an element in the lattice of semiconductor crystal is called doping. The impurity is introduced in the ratio of $1 : 10^6$.

Extrinsic Semiconductors

The doped semiconductor is called extrinsic semiconductor.

Examples of Pure or Intrinsic Semiconductor

Pure silicon and germanium are intrinsic semiconductors. These semiconductor elements have four valence electron. In crystalline form, the four electrons of the atom of Si or Ge form covalent bond with four of their neighbouring atoms and hence each atom of Ge and Si has eight electrons in the outermost orbit which is stable state.

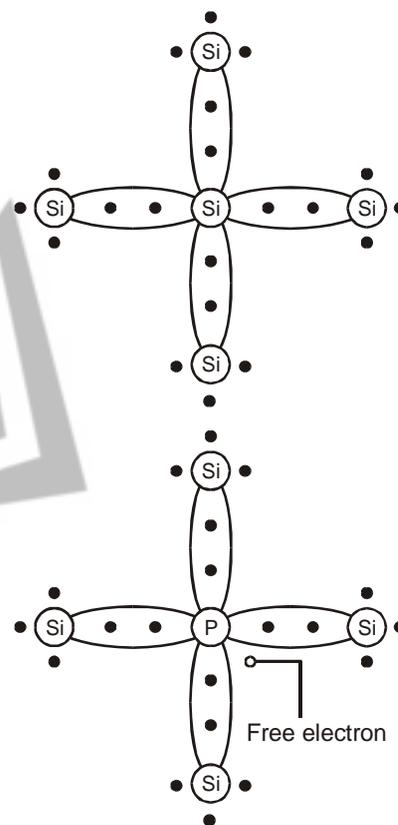
N-Type Substance

When a silicon or Ge crystal is doped with a pentavalent element like Arsenic, Antimony or Phosphorous, the configuration which results is shown in figure.

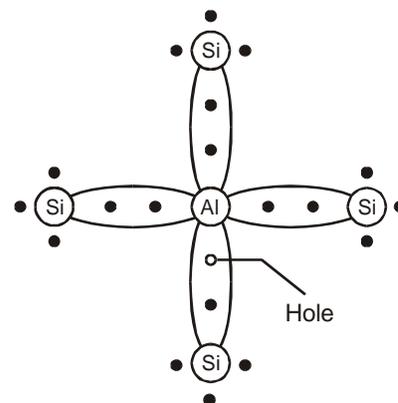
Four valence electrons of impurity atoms form covalent bonds with four neighbouring atoms of Si, while fifth electron which is unpaired behaves as free electron. Such a doped or extrinsic semiconductor is called N-type substance. The phosphorous atom is called a donor atom because it readily donates a free electron, which is thermally excited into the conduction band.

P-Type Substance

When a silicon or Ge crystal is doped with a trivalent element like Al, B, Ga or In, the configuration which results is shown in figure.



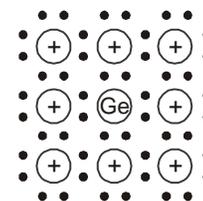
The three electrons of the impurity atom form covalent bond with three of the neighbouring Si atoms, while the one missing electron in the covalent bond with fourth Si atom is called a hole which in fact is vacancy where an electron can be accommodated. Thus a moving hole is equivalent to a moving positive charge. Such a semiconductor is called p-type semiconductor. The aluminium atom is called an acceptor atom because it is easy for the aluminium ion core to accept a valence electron from a nearby silicon atom, thus creating a hole in the valence band.



Q.9 Explain electrical conduction by electrons and holes in semi-conductors.

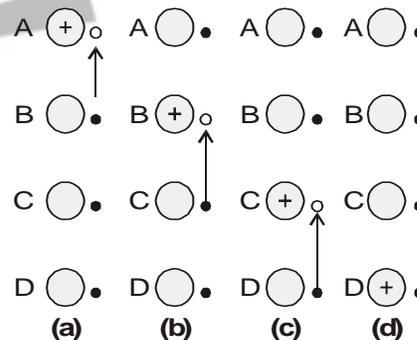
Ans. **ELECTRICAL CONDUCTION BY ELECTRONS AND HOLES IN SEMICONDUCTORS**

Consider a semi-conductor crystal lattice, e.g., Ge or Si as shown. The circles represent the positive ion cores of Si or Ge atoms, and the blue dots are valence electrons. These electrons are bound by covalent bond. However, at room temperature they have thermal kinetic motion which, in case of some electrons, is so vigorous that the covalent bond is unable to keep them bound. In



such cases the electrons break the covalent bond and get themselves free leaving a vacant seat for an electron, i.e., a hole. Thus whenever a covalent bond is broken, an electron-hole pair is created. Both the electrons and the holes move in the semi-conductor crystal lattice as explained below.

Consider a row of Si atoms in crystal lattice. Suppose a hole is present in the valence shell of atom A. As hole is a deficiency of electron, so the core of atom A would have a net positive charge. This attracts an electron from a neighbouring atom say B. Thus the electron moves from B to A and the hole (+ve charge) shifts to B. Now an electron is attracted from C to B and a hole is created at C and positive charge appears at C. This process is repeated between charge appears at C. This process is repeated between the atoms C and D with the result that the electron moves from D to C and the hole (+ve charge) appears at D.



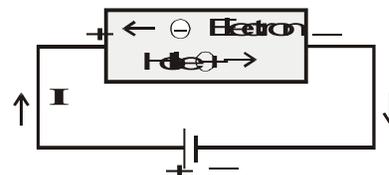
Thus we notice that if a hole is present in any valence shell, it cannot stay there but it moves from one atom to other with the electron moving in opposite direction. Secondly we notice that the appearance of hole is accompanied by a positive charge. Thus a moving hole is equivalent to a moving positive charge.

In this example we have considered a special case in which the electron and the hole are moving in a straight line. Actually their motion is random because positively charged core of the atom can attract an electron from any of its neighbouring atoms.

Thus, in semi-conductors there are two kinds of charge carriers; a free electron ($-e$) and a hole ($+e$).

When a battery is connected to a semiconductor, it creates an electric field across it due to which a directed flow of electrons and holes take place. The electron drift towards positive end, whereas the hole drift towards negative end. The current I flowing through the semiconductor is carried by both electrons and holes.

Current I is the sum of electronic current and hole current.

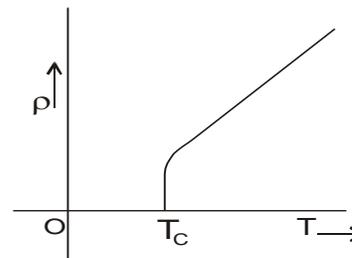


Q.10 What are the superconductors?

Ans. SUPERCONDUCTORS

There are some conductors whose resistivity becomes zero below certain temperature called critical temperature (T_C) is shown in resistivity temperature graph.

Below critical temperature, the conductor offers no resistance to the current and hence it becomes superconductor. Once the resistance of a material drops to zero, no energy is dissipated and the current once established, continues to exist indefinitely without the source of an emf.



Discovery of Superconductors

The first superconductor was discovered in 1911 by Kmaerlingh Onnes when it was observed that electrical resistance of Hg becomes zero at 4.2 K. Some other metals such as Al ($T_C = 1.18$ K), Sn ($T_C = 3.72$ K) and Pb ($T_C = 7.2$ K) also become superconductors at very low temperature. In 1986, a new class of ceramics material was discovered that becomes superconductor at temperature 125 K.

Recently a complex crystalline structure known as Yttrium Barium Copper Oxide ($YBa_2Cu_3 \cdot O_7$) have been reported to become superconductor at 163 K or -110°C by Prof. Yao Lian's Lee at Cambridge University.

Extensive research is going on to discover a superconductor at room temperature which will be new revolution in electrical technologies.

Technological Applications of Superconductors

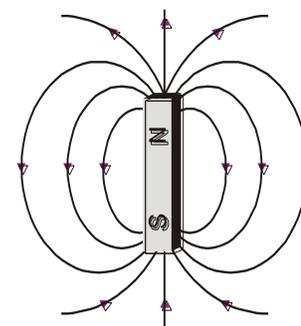
Superconductors have many technological applications such as in magnetic resonance imaginary (MRI), magnetic levitation trains, powerful but small electric motors and faster computer chips.

MRI uses strong magnetic fields produced by super conductive for remaining computer produces the image identifying tumours and inflamed tissues.

Q.11 Describe magnetic properties of solids. Describe the types of magnets.

Ans. MAGNETIC PROPERTIES OF SOLIDS

It is observed that field of a long bar magnet is like the field produced by a long solenoid carrying current and field of a short magnet. This similarity of fields tells that all magnetic effect may be due to circulating current. Electron orbits around the nucleus of an atom behave like current carrying loop which generate a small magnetic field. Motion of electron around the nucleus of two types



Long Bar magnet

- (1) Orbital motion about the nucleus.
- (2) Spin motion about its own axis.

The orbital and spin motions give rise to magnetic behaviour of an atom.

Magnetic Dipole

As there are number of electrons in an atom, their currents or spins may be so oriented, or aligned so as to strengthen the effect of each other. An atom in which there is resultant magnetic field, behaves like a magnet and is called magnetic dipole.

Paramagnetic Substances

If the spin and orbital axis of electrons in an atom are so oriented that their fields support each other and the atom behaves like a tiny magnet, then substances with such atoms are called paramagnetic substances.

Diamagnetic Substances

Those substances in which the magnetic field produced by orbital and spin motion of the electron may cancel each other, are called diamagnetic substances. e.g., the atoms of water, Cu, Bi and Sb.

Ferromagnetic Substances

There are certain substances. e.g., Fe, Cd, Ni chromium dioxide and Alnico (an Al-iron-Ni and cobalt alloy) in which atoms co-operate with each other in such a way so as to show strong magnetic effects, are known as ferromagnetic substances.

Recent studies of ferromagnetic have shown that there exist small regions called domains. The domains are of microscopic size of the order of millimeters but they contain 10^{12} to 10^{16} atoms. Within each domain the magnetic fields of all the spinning electrons are parallel to one another. i.e., each domain is magnetized to saturation. Each domain behaves as a small magnet with its own north and south poles.

In unmagnetized iron, the domains are oriented in a disorderly fashion, so that net magnetic effect of a sizeable specimen is zero. However if on specimen is placed in external magnetic field, as that of a solenoid, the domains line up parallel to linear of external magnetic field and entire specimen is saturated.

Electromagnet

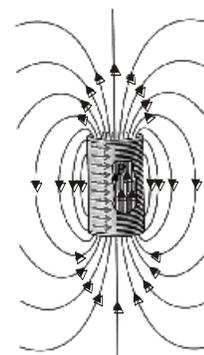
The combination of a solenoid and a specimen of iron inside it, makes a powerful magnet and is called electromagnet.

Soft and Hard Magnetic Materials

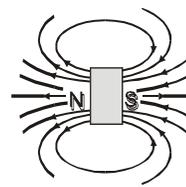
Iron is soft magnetic material. Its domains are easily oriented on applying an external field and also readily return to random positions when the field is removed. This is desirable in electromagnet and in making transformer core.

However in *steel*, the domains are not so easily oriented to order. They require very strong external magnetic field. But once oriented, retain the alignment. Thus steel makes a good permanent magnet and is known as hard magnetic material. Another hard magnetic material is special alloy Alnico V.

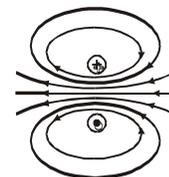
Curie Temperature



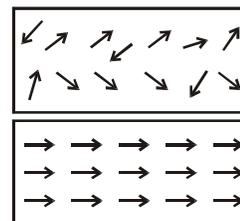
Solenoid



Short Bar magnet



Magnetic field of a current loop

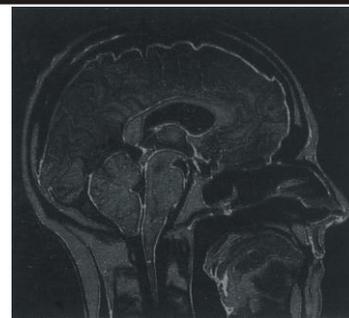


Do You Know?

Special alloy Alnico V is used in making permanent magnets.

Thermal vibrations tend to disturb the orderliness of domains. Ferromagnetic materials preserve the orderliness at ordinary temperature. When heated, they begin to lose their orderliness due to increased thermal motion. This process begins to occur at a particular temperature (different for different materials) called Curie temperature. The Curie temperature for iron is 750°C .

For Your Information



Magnetic Resonance Imaging (MRI) uses strong magnetic field produced by superconducting materials for scanning. Computer processing produces the image identifying tumors and inflamed tissues.

Q.12 Explain Hysteresis loop.

Ans. HYSTERESIS LOOP

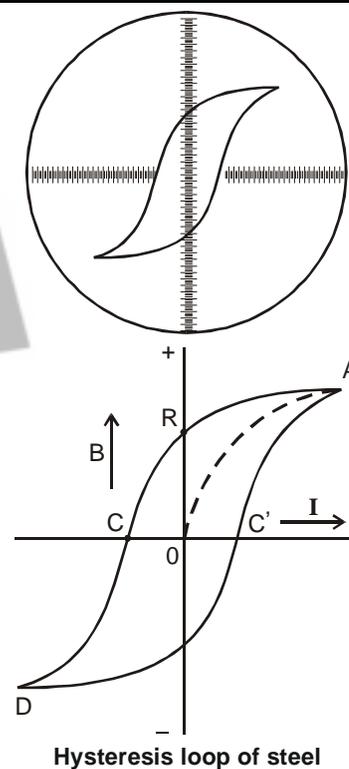
To investigate a ferromagnetic material, a bar of that material such as iron is placed in an alternating current solenoid. When the alternating current is at its peak value, it fully magnetizes the specimen in one direction and when the current is at its negative peak, it fully magnetizes it in opposite direction. Thus as the alternating current changes from its positive peak value to its negative peak value, the specimen undergoes a complete cycle of magnetization. The flux density versus magnetization of the specimen for various values of magnetizing current of solenoid is plotted by a CRO. The main features of the experiment are

(1) Hysteresis

The portion OA of the curve is obtained when magnetizing current I is increased and AR is the portion when current is decreased. It may be observed that the value of flux density is always greater when the current is decreasing than it is increasing. i.e., magnetism lags behind magnetising current. This phenomenon is known as Hysteresis.

(2) Saturation

The magnetic flux density increases from zero to a maximum value and the material is said to be magnetically saturated.



(3) Remanence or Retativity

When current is reduced to zero, the material still remains strongly magnetized represented by point R on the curve. It is due to tendency of domains to stay partly in line, once they have been aligned.

(4) Coercivity

To demagnetise the material, the magnetising current is reversed and increased to reduce the magnetization to zero. This is known as coercive current represented by C on the curve. The coercivity of steel is more than that of iron as more current is needed to demagnetize it. Once the material is magnetized, its magnetisation curve never passes through origin. Instead, it forms the closed loop ACDC'A, which is called *Hysteresis loop*.

(5) Area of Loop

The area of the loop is a measure of energy needed to magnetize and demagnetize the specimen during each cycle of the magnetizing current. This is the energy required to do work against internal friction of domains. This work, like work that is done against friction, is dissipated as heat. It is called hysteresis loss.

Hard magnetic materials like steel cannot be easily magnetized or demagnetized, so they have large loop area as compared to soft magnetic material such as iron which can easily be magnetized. The energy dissipation for iron is less than steel.

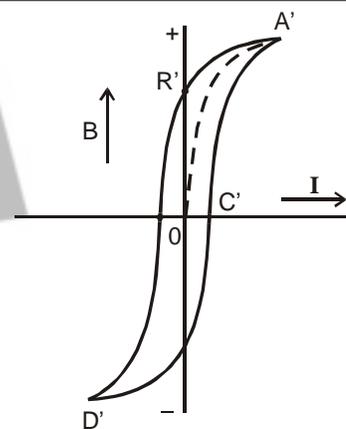
Note: A material with high retentivity and large coercive force would be most suitable to make a permanent magnet. The error of electromagnets used for A.C. should have narrow hysteresis curves of small area to minimize the waste of energy.

For Your Information

Squids (or super-conducting quantum interference devices) are used to detect very weak magnetic field such as produced by the brain.

Do You Know?

Magnets made out of organic materials could be used in optical disks and components in computers, mobile phones, TVs, radios, generators and data storage devices. Circuits can make use of ceramic magnets that do not conduct electricity.



Hysteresis loop of iron



A bullet train is lifted above the rails due to magnetic effect, thus friction is reduced to minimum and speed can be enhanced up to 500 kmh^{-1} .

SOLVED EXAMPLES

EXAMPLE 17.1

A steel wire 12 mm in diameter is fastened to a log and is then pulled by tractor. The length of steel wire between the log and the tractor is 11 m. A force of 10,000 N is required to pull the log. Calculate (a) the stress in the wire and (b) the strain in the wire. (c) How much does the wire stretch when the log is pulled? ($E = 200 \times 10^9 \text{ Nm}^{-2}$)

Given Data

$$\text{Diameter of steel wire} = 12 \text{ mm} = 12 \times 10^{-3} \text{ m}$$

$$\begin{aligned} \text{Radius of wire} &= r = \frac{d}{2} = \frac{12}{2} \times 10^{-3} \\ &= 6 \times 10^{-3} \text{ m} \end{aligned}$$

$$\text{Length of wire} = l = 11 \text{ m}$$

$$\text{Force} = F = 10,000 \text{ N}$$

$$\text{Modulus of elasticity} = E = 200 \times 10^9 \text{ Nm}^{-2}$$

To Find

- (a) Stress in the wire = ?
 (b) Strain in the wire = ?
 (c) Change in length = Δl = ?

SOLUTION

(a) Calculation of Stress

$$\text{Stress } (\sigma) = \frac{F}{A} = \frac{10,000}{\pi r^2}$$

$$\sigma = \frac{10,000}{3.14 \times (6 \times 10^{-3})^2}$$

$$\sigma = 88.46 \times 10^6 \text{ Nm}^{-2}$$

$$\boxed{\sigma = 88.46 \text{ MP}_a}$$

(b) Calculation of Strain

$$E = \frac{\text{Stress}}{\text{Strain}}$$

$$\text{or Strain} = \frac{\text{Stress}}{E} = \frac{88.46 \times 10^6}{200 \times 10^9}$$

$$\text{Strain} = \frac{88.46 \times 10^{6-9-2}}{2}$$

$$\text{Strain} = 44.23 \times 10^{-5} = 4.4 \times 10^{-4}$$

$$\boxed{\text{Strain} = 4.4 \times 10^{-4}}$$

(c) **Calculation of Δl**

As
$$\text{Strain} = \frac{\Delta l}{l}$$

$$\Delta l = \text{Strain} \times l = 4.4 \times 10^{-4} \times 11$$

$$\Delta l = 4.84 \times 10^{-5} = 4.84 \times 10^{-3} \text{ m}$$

$$\boxed{\Delta l = 4.84 \text{ mm}}$$

Result

(a) Stress in the wire = $\sigma = 88.46 \text{ MP}_a$

(b) Strain in the wire = 4.4×10^{-4}

(c) Change in length = $\Delta l = 4.84 \text{ mm}$

