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# CLASSIFICATION OF MATERIALS

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## 1.1 Properties of Materials

Various types of materials are required for the manufacture of any engineering goods. These materials have different properties and hence serve specific functions. It is, therefore, necessary that the persons responsible for the selection of materials are familiar with the properties of various materials and the right techniques to be used in working with them. In manufacturing of machines, selection of right type of materials and the techniques of handling or working with them during fabrication is fundamental to the total process. Development in the designs of machines, devices and systems has largely depended upon the development of better quality materials. Improved quality engineering materials have led to the reduction in size of machines and devices, improved efficiency and longer durability.

The properties of materials are divided into three categories. They are namely, physical properties, chemical properties, and technological properties. There cannot be any strict demarcation between these three categories of properties. For example, technological properties would largely depend upon physical and chemical properties. One of the technological properties, say, machinability (whether the material can be cut on machines) depends upon hardness, brittleness, strength, etc.

A large number of technical terms are used in specifying the properties of a material. It is important to understand the meaning of these terminologies to be able to read and write specifications of engineering materials required for a specific purpose. The various properties of materials and short explanation of each of them are presented before taking up the classification of materials.

Figure 1.1 shows different properties of materials.

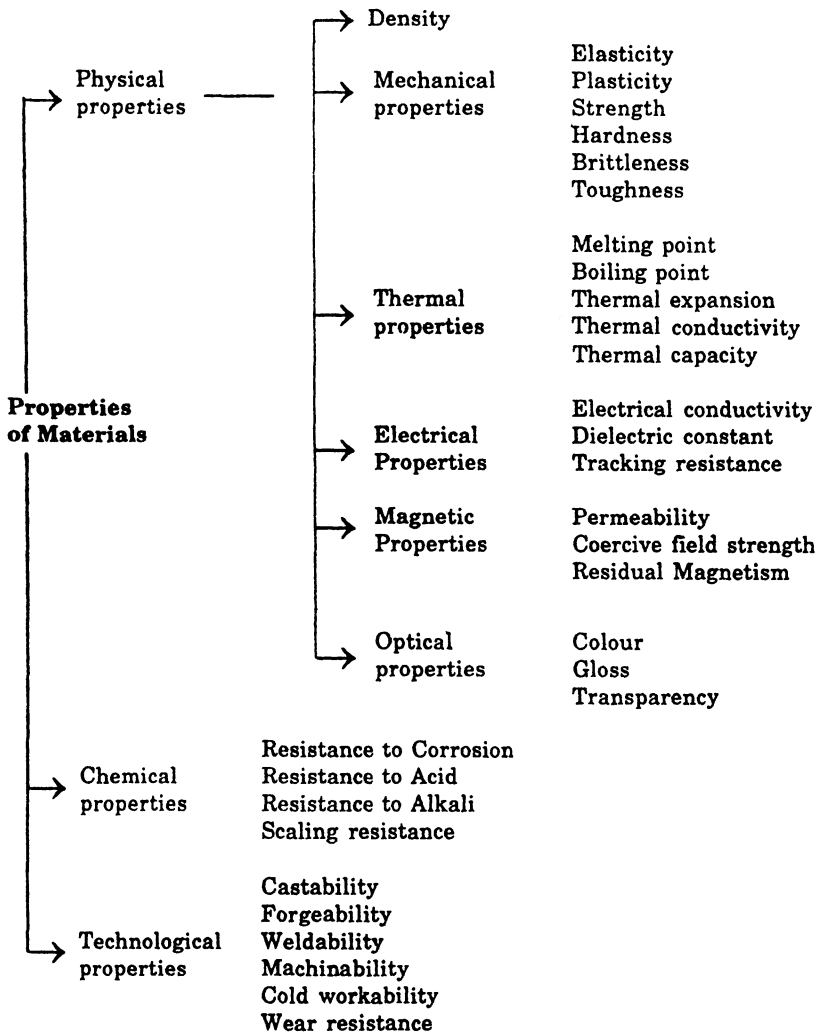


Figure 1.1 Classification of Properties of materials.

The meaning of various properties indicated in figure 1.1 are given as follows.

**Density** : It is the ratio of mass of the material to its volume.

**Elasticity** : It is the property of a body of material of resuming its original form and dimensions when the force acting upon it is removed. If the force is sufficiently large for the deformation to cause a break in the molecular structure of the body or material, it loses its elasticity and the elastic limit is said to have been reached.

**Plasticity** : It is the property of a body or material of undergoing permanent deformation under the effect of force, *i.e.* of not returning to its original form when the force is removed.

**Strength** : It is the resistance of the material to breaking. Different types of strength are tensile strength, compression strength, shearing strength, torsional strength, etc.

**Hardness** : It is the property of resisting penetration by another material.

**Brittleness** : It is the property of breaking of a material without changing its shape.

**Toughness** : It is a property just opposite to brittleness. A tough material or workpiece will undergo considerable plastic deformation before breaking.

**Melting point** : It is a temperature at which the solid material begins to melt. Melting points are normally quoted for standard atmospheric pressure, *i.e.* 760 mm of mercury.

**Boiling point** : The temperature at which a liquid boils freely and begins to turn into gas. Boiling points are normally quoted for standard atmospheric pressure.

**Thermal Expansion** : It is the increase in volume of a material due to rise in temperature. Coefficient of linear expansion is the measure of thermal expansion of solid material.

**Thermal conductivity** : It is the ability of a material to 'transmit heat'.

**Thermal capacity** : It is the amount of heat required to raise the temperature of a material.

**Electrical conductivity** : It is the reciprocal of resistivity or specific resistance of a conductor.

**Dielectric constant** : It is the ratio of the capacitance of a capacitor with a specified medium (dielectric material) between the plates, to the capacitance of the same capacitor with free space between the plates. Thus, it is the property of the dielectric material that causes the difference in the value of the capacitance, physical dimensions *viz* plate area and distance between the plates remaining the same.

**Tracking Resistance** : It is the resistance of an insulating material to surface currents.

**Permeability** : It is the ratio of the magnetic flux density in a medium to the external magnetic field strength that induces it. **Relative permeability** is the ratio of the permeability of a substance to the permeability of free space.

**Coercive field strength :** It is that strength of the magnetizing force that is required to destroy or remove residual magnetism from a magnetic material undergoing a hysteresis cycle.

**Residual Magnetism :** It is the amount of magnetism retained in a magnetic material when the magnetizing force producing magnetism is reduced to zero.

**Colour :** The visual sensation resulting from the impact of light of a particular wave length on the cores of the retina of the eye.

**Gloss :** It represents the brightness of a material.

**Transparency :** The quality of a material of permitting the passage of light in such a way that objects can be seen clearly through the substance.

**Resistance to corrosion :** It is the resistance of a material, specially of metals, to getting damaged by surface chemical action due to the action of moisture, air or chemicals.

**Castability :** Ability of the material being given a particular shape by casting.

**Forgeability :** Ability of the material being given a desired shape by forgeing.

**Weldability :** Ability to join two metal surfaces by raising their temperature sufficiently to melt and fuse them together.

**Machineability :** Means whether the material can be cut on machines.

**Wear Resistance :** It is the resistance of a material to surface erosion *e.g.* due to friction.

In addition to the above properties one has to see the availability of a material having the desired properties and the cost of the material.

While selecting a material one has to compare the requirements in the actual application, and the properties of the material. Many a times a material may have a number of good properties but due to one poor property, the material cannot be used for a specific application. For example, conductivity of silver is very good and may be chosen as a conductor material for carrying current from one place to the other. But, because of its prohibitive cost, is not used for transmission of current. Instead, a comparatively less conductive material like copper and Aluminium is used. Mica having very good insulating property (a property by virtue of which it prevents flow of current through it) cannot be used every where because the material is brittle.

Research has led to the development of new materials having better properties and thus has replaced many of the earlier used

materials. A constant search for new materials will lead to discovery of new machines, devices and techniques to make systems more economical and efficient.

## 1-2 General Classification Materials

Materials can generally be classified into metals and non metals as shown in figure 1-2.

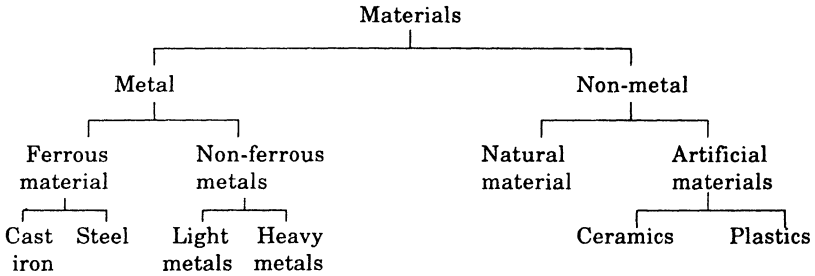


Fig. 1-2 General Classification of materials.

Metals are fundamentally different in their structure and properties from other materials. The crystalline structure of metals is the basis of their characteristic luster. Characteristic properties of most materials, amongst others, are high strength and toughness, good alloyability, and high thermal and electrical conductivity. Ferrous materials like iron and steel are the most commonly used working materials. Apart from copper, gold and their alloys, all metals are greyish white in colour, with a bluish tint in some cases.

Non-metals like Helium, Boron, Carbon, Nitrogen, Chlorine, etc. can be classified in a number of ways. Nearly all non-metals can be used as insulators because they have relatively high specific resistances (because of absence of conducting electrons). Non-metals are also used as alloying components.

Non-metallic natural materials are produced by processing and shaping new materials. For example cotton tape is natural processed insulating material.

## 1-3 Classification of Materials used in Electrical and Electronics Engineering

Materials used in the field of electrical and electronics engineering can be classified on the basis of functions they perform in various applications.

Materials used to carry electricity from one place to another through flexible cables, transmission lines, underground cables, windings of electrical machines and instruments, current carrying coils, etc. are called **conducting materials**. Conducting materials like copper, aluminium are used for carrying current without much

loss of power in them. Conducting materials are also used in applications like filament of incandescent lamps, rheostats, potentiometers, as heating elements in water and room heaters, etc. Materials like tungsten, nicrome, platinum are some of these materials having characteristics like high resistivity, high melting point, etc.

Materials used to obstruct the flow of electricity like mica, rubber, paper, bakelite, porcelain, PVC, glass, etc. are called **insulating materials**. Such materials are used in applications *e.g.* in wires or cables used for house wiring where the conductor carrying current is covered with a PVC insulation so that current does not flow in other directions than through the wire and to the appliances connected to the circuit (any extremely small amount of current that might flow through the insulation is called leakage current). Porcelain insulators are used to hang transmission lines on towers so that current only flows through the transmission lines and there is practically no leakage current flowing to the earth through the body of the transmission tower.

Materials like air, paper, oil, mica, and oxides of certain metals used to store electricity are called **dielectric materials**. These materials are used in capacitors as dielectric material placed in between the two plates. Dielectric materials are essentially insulating materials. However, the function of an insulating material is to resist the flow of electric current through them, and that of a dielectric material is to help store electrical energy.

Materials like iron, steel, and certain alloys of iron that can be magnetized are called **magnetic materials**. When magnetized by applying a magnetizing current flowing through a winding placed around these materials, a magnetic field is established around them. Magnetic materials are used as core material in transformers, electrical machines and appliances, chokes, relays, etc.

Materials whose resistance decreases with rising temperature and in the presence of impurities are called **semiconducting materials**. Germanium, Silicon, Selenium, etc. are the examples of semiconducting materials. At absolute zero temperature they would allow no passage of current through them. At normal temperatures, however, the resistance to flow of current will decrease. Semiconducting materials are used to create semiconductor junction, a plane that separates two layers of a semiconductor each of which have different electrical characteristics. Semiconducting materials are extensively being used in electronic industry in making diodes, transistors, controlled rectifiers, etc.

Materials that are used to provide mechanical support like frame, shaft, enclosures, containers, bearings, etc. are called **structural materials**. Materials used for connecting together two pieces

(soldering, welding, etc.), are called **jointing materials**. They are widely used in electrical and electronic industry. Certain adhesives are also used as **bonding materials**. All these materials we will call for the purpose of presentation in this book, as **Materials for special purpose**.

To summarize, the following are the classes of electrical and electronic engineering materials that would be considered :

- Conducting Materials ;
- Semi conducting materials ;
- Insulating materials ;
- Magnetic materials ; and
- Materials for special purpose

To understand how materials behave as conducting, Semiconducting, insulating or magnetic materials one has to refer to atomic structure of materials and the type of interatomic bonding that exist in them. A brief explanation of the above is presented in the next section.

#### 1.4 Atomic Structure

Matter is composed of large number of basic substances called atoms. An atom is defined as a substance or particle that can neither be further broken up nor be created by ordinary chemical means. Each atom of a matter consists of three different type of particles. These are : Protons, Neutrons, and Electrons.

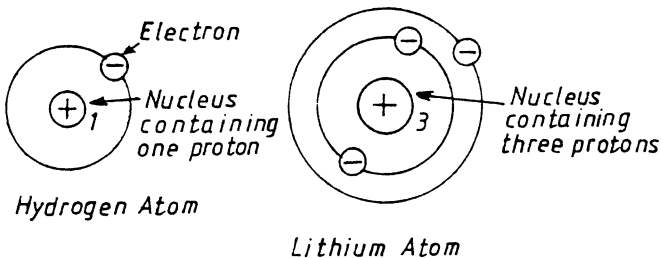


Fig. 1-3 Structure of Hydrogen and Lithium atoms shown in a simplified form.

The central of an atom is termed as Nucleus. The nucleus consists of particles called protons and neutrons. The protons are positively charged particles, while neutrons have no charge. Therefore, the nucleus of atom is positively charged. The electrons are negatively charged particles. Charge of an electron is equal in magnitude to the positive charge of a proton. In an atom electrons revolve round the nucleus in certain well defined paths, called **shells**. The number of electrons in any atom is equal to the number of protons in

its nucleus. Number of protons in the nucleus of any atom is equal to the atomic number of that atom. For example number of protons in the nucleus of Hydrogen and Lithium atoms is 1 and 3 respectively, their atomic numbers therefore, are, 1 and 3 respectively. See figure 1.3.

The electrons are very light in weight as compared to protons and neutrons. In fact, electron is the lightest particle known. Its mass is  $1/1850$  times that of proton. The neutron has mass and size equal to that of proton. Thus weight of an atom is entirely due to the protons and neutrons in the nucleus.

The electrons, moving in their shells around the nucleus, are kept in the atom by the attraction exerted on them by the positive nucleus. The electrons near the nucleus are firmly held and therefore it is difficult to pull them out of the atom. The electrons moving in shells which are away from the nucleus of an atom require the least energy to remove them from the atom. This is because these electrons are not only very far from the attracting nucleus, but also experience repulsive forces from the electrons which are situated in between the outermost shell and the nucleus.

### 1.5 Behaviour of Electrons in Atoms

To study the characteristics of an element, one has to study the **electronic configuration or electronic structure** of the atoms constituting that element. To analyse the electronic structure of atom one has to know the following :

- (i) Concept of Atomic orbital
- (ii) Quantum Numbers
- (iii) Pauli's Exclusion Principle
- (iv) Shapes of orbitals
- (v) Energy level diagram for electrons in an atom

These are explained as follows :

#### (i) Concept of Atomic Orbital

According to classical Bohr's theory, electrons revolve in well defined paths called orbits. However, **uncertainty principle** and **dual nature of matter** give a big blow to the concept of Bohr's model.

According to uncertainty principle "position and velocity of a fundamental particle like electron cannot be defined exactly", *i.e.* there is uncertainty in the position and velocity of electron.

And, dual nature of matter means, an electron exhibits both **particle nature** and **wave nature**. According to this approach, one cannot simply say that an electron exists at a particular point, instead it exists in certain regions in the space around the nucleus. The most probable regions in space around the nucleus is called orbitals.



Thus an orbital may be defined as a region in space around the nucleus where probability of finding the electron is maximum. Large numbers of electron orbitals is possible in an atom. One orbital can have 2 electrons.

**(ii) Quantum Numbers**

To describe each electron of an atom in different orbitals, we need a set of three numbers, known as quantum numbers. These are designated as  $n$ ,  $l$  and  $m$ . In addition to these three numbers, another quantum number is also needed which specifies the spin (electrons also revolve around their own axis which is called spinning) of the electron. They are discussed as follows :

**(a) Principal quantum number ( $n$ ):** This quantum number determines the main energy shell or level in which an electron is present. It is denoted by ' $n$ '. It can only have whole number values, starting from 1. This quantum number is also regarded as shell number. Shell with  $n = 1$  is called the first shell. The various shells are designated either as  $n$  equal to 1, 2, 3, ..... or as K, L, M, N, ...

As the value of  $n$  increases, the distance of an electron in that shell from the nucleus increases. Principal quantum number gives the average distance of an electron from the nucleus. Also, as the value of  $n$  increases the energy of an electron in that shell increases. A shell can have a number of sub-shells.

**(b) Angular quantum number ( $l$ ):** This quantum number determines the angular momentum of the electron. This is denoted by ' $l$ '. The value of  $l$  gives the sub shell in a given principal shell to which an electron belongs. It can have positive integer values from 0 to  $(n-1)$ , where  $n$  is the principal quantum number. As for example, for  $n = 1$ ,  $l$  has only one value, i.e.,  $l = 0$  ;

The number of subshells in each shell of an atom are shown in table 1-1.

**Table 1-1. Number of sub-shells in each shell of an atom**

$n$	$l$	Sub-shell Designation	No. of sub-shells in a shell
1	0	1s	One
2	0	2s	Two
	1	2p	
3	0	3s	Three
	1	3p	
	2	3d	
4	0	4s	Four
	1	4p	
	2	4d	
	3	4f	

The subshells within a given shell differ slightly in energy.

For  $n = 2$ ,  $l$  has two values, *i.e.*  $l = 0, 1$ ; and

For  $n = 3$ ,  $l$  has three values *i.e.*  $l = 0, 1, 2$ .

The various sub shells or values of  $l$  are also designated by letters s, p, d, f, ... as :

Value of  $l = 1, 2, 3 \dots$

Designation = 's' 'p' 'd' 'f' ...

(c) **Magnetic quantum number** : Under the influence of earth's magnetic field sub-shells (designed by  $l$ ) get oriented in a number of directions. These directions are specified by magnetic quantum number,  $m$  which can have values  $-1$  through  $0$  to  $+1$ . For example,  $l = 0$  *i.e.* the *S* subshell will have only one orientation since value of  $m$  is  $0$ . For  $l = 1$ ,  $m$  will have three values *i.e.*  $-1, 0, +1$ . This means *p* sub-shell can have three orientations.

This may be noted that these orientations, in fact indicate the number of orbitals in a sub-shell.

(d) **Spin quantum number** : It is observed that the electron in an atom is not only revolving around the nucleus but also are spinning around its own axis.

Spin quantum number describes the spin orientation of the electron. Since electron can spin in only two ways *i.e.* clockwise or anticlockwise, the spin quantum number can take only two values which is represented as  $+1/2$  *i.e.* clockwise and  $-1/2$  *i.e.* anticlockwise.

Thus, the four quantum numbers describe the position of electrons in an atom by specifying main shell ( $n$ ), subshell ( $l$ ), the orientation of the orbital ( $m$ ), and direction of spin. In other words, these quantum numbers help to address an electron.

### (iii) **Pauli's Exclusion principle**

It states that no two electrons in any orbital can have the same values of all the quantum numbers. Following this principle one can calculate the number of electrons in each shell. For example, for the first shell we have  $n = 1, l = 0, m = 0$ .  $l = 0$  indicates that there is only one subshell and  $m = 0$ , indicates that there is only one orientation of the sub-shell. Hence, the number of orbital is one and therefore maximum number of electrons in the first shell is 2.

For the second shell,  $n = 2, l = 0, 1$ , (*i.e.* *S, P*). The orientation of the 0 subshell on one and 1 sub-shell is  $-1, 0, +1$  *i.e.* three. Thus total number of orbitals is equal to four. Maximum number of electrons is then 8. Similarly, it can be seen that in the third and fourth shells, maximum number of electrons would be 18 and 32. However, for an atom to have stable electronic structure, only 8 electrons are required in the outermost shell.

(iv) **Shapes of orbitals**

It has been known that probability of finding the electron does not become zero even at a large distance from the nucleus. It is therefore not possible to draw any sort of geometrical figure around the nucleus that will enclose a region of one hundred percent probability.

**Shape of s-orbitals :** We know that the orbital for which  $l = 0$  are called s-orbital. For  $l = 0$ , there is only one possible value of  $m$  i.e.  $m = 0$ , i.e. only one possible orientation. This means that the probability of finding the electron at a particular distance from the nucleus is the same in all directions. In other words, the electron distribution in s-orbital is spherically symmetrical around the nucleus.

**Shape of p-orbitals :** Each p-subshell is characterised by  $l = 1$ . The possible values of  $m$  are +1, 0 and -1. This means that there are three p-orbitals in each p-subshell. They are oriented along the three directions and are designated by  $px$ ,  $py$  and  $pz$ .

(v) **Energy level diagram**

The relative energies of various orbitals can be shown by an arrangement known as **energy level diagram**. In case of multi electron atoms, the energy of orbitals, having the same value of  $n$  but different value of  $l$ , are different. This means that energy of the orbitals depends upon the value of 'n' as well as 'l'. The energy of the different orbitals in the increasing order is given at 1S, 2S, 2p, 3S, 3p, 4S, 3d, 4p, 5S, 4d, 5p, 6S, 4f, 5d, 6p, 7S. According to Aufbau principle, the orbitals should be filled in increasing order of their energies. So, orbitals are filled with electrons in the order given above.

Since most materials in engineering are either solids or liquids, it is necessary to understand the forces that hold the atoms of the element together when this solid or liquid is formed. Many physical properties such as strength, melting point, electrical conductivity etc. depend on these forces. Hence these forces will, under normal conditions, be quite strong.

Consider the mechanism that give rise to interatomic forces. Interatomic forces are caused by electrons in the shells of the atoms forming the solid. In particular, they are normally due to the electrons in the outermost shell of the atom.

Atoms with eight electrons in their outer shell (completely filled 's' and 'p' subshells) such as Neon (2, 8), Argon (2, 8, 8), Krypton (2, 8, 18, 8) etc. have very little attraction to each other. Helium (2) is similar except that only 2 electrons are needed to fill the first shell. These elements possess a completely filled shell without forming an ion i.e. they are naturally very stable.

Most other elements, beside the noble gases, do not have this stable arrangement of 8 electrons in their outer shell. These elements attempt to reach this stable structure by one of the following three mechanisms :

(a) **Losing electrons** : The electronic structure of potassium having an atomic number 19, is given by  $1S^2 2S^2 2p^6 3S^2 3p^6 4s^1$ . Potassium can achieve a closed shell structure by losing the  $4s^1$  electron leaving the potassium ion with the stable electronic structure *viz*  $1S^2 2S^2 2P^6 3S^2 3p^6$  which is the same as that of argon.

(b) **Gaining electrons** : Elements such as chlorine having an atomic number 17, whose electronic structure is  $1S^2 2S^2 2P^6 3S^2 3p^5$  can have a stable filled shell if they receive one electron resulting again in the Argon electronic structure of  $1S^2 2S^2 2p^6 3S^2 3p^6$ .

(c) **Sharing electrons** : Certain elements in the periodic table such as silicon (atomic number, 14) have more than two but less than six electrons in their outermost shells. The elements of groups III, IV and V (see Annexure I) do not lose or gain a large number of electrons to achieve a stable electronic structure. These atoms, instead, share the electrons. For example, one atom of silicon will share its 4 electrons with any other silicon atoms.

Modification of the electronic structure results in strong forces which keep the atoms together to form a solid. These attractive forces between atoms are called bonds.

## 1-6 Atomic Bonds

The bond between atoms make it possible to combine them to form a solid.

Inter atomic bonds are of three main types :

- (i) Ionic bond
- (ii) Covalent bond
- (iii) Metallic bond.

We will discuss all these three types of bonding one by one, and then explain various types of materials.

### 1-6-1 Ionic Bond

The ionic bond is due to the force of attraction between a positive and a negative charge. Groups I and II elements of the periodic table have one and two electrons in the outer shell. Study of Electronic Configuration reveals that electronic structures similar to the inert gases with completely filled outer shell are very stable. The group I and group II elements release the one or two electrons from their partly filled shells so that the resultant electronic configuration is just like that of an inert gas. Atoms which lose electrons and become positive ions are called electro positive atoms and such elements are

called electro positive elements.

Atoms that form negative ions by gaining electrons are called electro negative atoms and such elements are called electro negative elements. Elements from groups VI and VII of the periodic table have six or seven electrons in their outer-most shell. These elements can achieve the stable shell structure as of an inert gas, by either losing many electrons or by receiving one or two electrons. It may be expected that these elements would readily gain a few electrons in preference to having to lose six or more electrons, since this process will require more energy and hence the idea is against the concept of stability. Therefore by accepting electrons, these elements achieve the stable electronic configuration of the inert gases.

Electropositive elements have tendency to give up their electrons while electronegative elements have tendency to receive electrons. Such different types of elements will easily become ions if they are brought together. For example, an electro positive element like Na (Sodium) with an electronic configuration of  $\text{Na} = 1S^2 3S^2 2p 3S$  will lose its single electron in the 3s shell to Fluorine (an electro negative element) with an electronic structure of  $\text{F} = 1S 2S 2p$ . The resultant sodium ion will be positively charged due to the loss of electron while the fluorine ion will be negatively charged due to the extra electron it now possess. Since these ions are of opposite charge they will electrostatically attract each other causing the sodium ion to move closer to the fluorine ion. This attraction will bring them closer and closer until the electrons of the outer shells of the ions begin to repel each other.

Now let us consider the reasons for ionic bonding in terms of total energy of the molecule. A universal law of the nature is that any system will try to minimise its energy. In other words, an ionic molecule will only be formed if the total energy of the molecule is less than the total energy of separate atoms forming the molecule.

Now when positively charged and negatively charged ions are formed, the attractive nature of the opposite charges causes them to move closer. When opposite charges move forward to each other, their potential energy gets reduced.

When the ions get closer the electrons of the two ions begin to repel each other, thus trying to create an increase in their potential energy. It is necessary to give some energy to form ions. The sum of energy required or added to form ions plus the increase in energy due to repulsive forces of electrons of ions is much less than the increase in energy that would take place when the two ions get closer. The ionic molecule is hence formed because the two atoms are able to minimize their total energy by bonding. The difference in energy between the unbounded and the bounded atom is the energy that one would have

to give to ionic molecule in order to break the bond. This energy is called the bond strength. Due to electro static nature of the ionic bonds, it is possible for a bond to be formed in any direction since the two ions basically look like two charged spheres. The ionic bond is hence said to be non-directional.

### 1-6-2 Covalent Bond

For the elements of groups III, IV and V of the periodic table, the energy required to form the ions is usually very large since it involves removing three or more electrons from the outer shell. The decrease in potential energy if ions are attracted is, in this case, less than the energy required to ionise the elements. Hence these elements do not form an ionic bond, but rather increase the number of electrons in their outermost shell **by sharing** electrons.

Carbon, whose atomic number is 6, a group IV element, has an electronic structure ( $C = 1s^2 2s^2 2p^2$ ) that has two electrons in the completely filled first shell and four electrons in the second. For getting a stable electronic structure, the second shell would require to gain 4 more electrons.

As distribution of charge of an unfilled shell is not spherically symmetric, the electron clouds of carbon atom will be pointing out in some particular direction depending upon the wave function and probability of charge. In the case of carbon it may be seen that, electrons are directed along a particular direction (axis). The overlapping of other electron clouds (*i.e.* sharing) can be only take place along these directions. In other words, an atom trying to form a bond with carbon atom can only do so in a certain direction in which electron clouds are present.

If a hydrogen atom tries to come closer to another atom from a direction in which there is no electron cloud, then no overlapping of electron orbitals will be possible. Hence, bonding cannot take place in other directions since electrons are not being shared.

The reason behind the sharing of electron orbitals by two atoms is because their total energy is lowered. The covalent bonds are only formed if there are half filled shells. Furthermore, unlike the ionic bonds, covalent bonds are directionally oriented since the electrons can only be shared along certain directions.

### 1-6-3 Metallic Bond

From the periodic table it may be seen that the majority of elements are metals. These materials are generally good conductors of heat and electricity. The reason for these physical properties is largely due to the way in which these metals (materials) form a very special type of bonding called metallic bonding. In general, all these elements have a small number of valence electrons in the outer shell.

Consider an element having an electronic configuration of  $1s$ ,

$2s$ ,  $3s$ ,  $3p$   $3d$ ,  $4s$ . It has two electrons in the outermost shell. These electrons are loosely bound to nucleus. These valence electrons can be removed easily, resulting in the formation of a metal ion. It is found that the path of these loosely bound valence electrons is spread out so much that, the average electron radius of these electrons is greater than the inter-ionic separation. It thus become difficult to identify which electron belongs to particular atom.

In a metal when such freely moving electrons come closer to a positively charged nucleus (see figure 1.4 (a), the total energy of the system is lowered resulting in a bond.

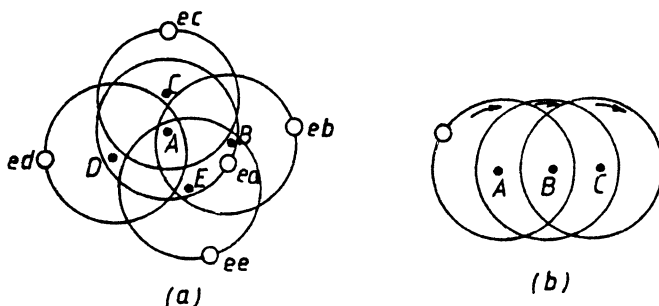


Fig. 1.4 (a) Formation of atomic bond due to freely moving electrons coming closer to positively charged nucleus.

(b) Metallic bond illustrated through simplified diagram.

Now, let us examine the conductivity of metals forming such a bond. For clear understanding, let us refer to figure 1.4 (b). The free electron from atom  $A$  when comes near another atom, say  $B$ , it can take the outer most shell or orbit of atom  $B$ . This electron further can move into the orbit of another atom  $C$  the orbit of which is at the same energy level of that of  $B$ . In this way an electron can travel through the solid. In the absence of any electric potential, movement of electron in the metal is in random direction. However, by applying an electric potential across the metal, electron can be made to travel towards the positive terminal through the metal. Such materials forming metallic bond do therefore have good conductivity.

## 1.7 Classification of Materials according to Atomic Bonds

Materials may be classified into Conducting, Semiconducting or Insulating materials depending upon the type of atomic bonds they possess. Atomic bonds in these materials and resultant behaviour are discussed as follows.

### 1.7.1 Conducting Materials

Materials which are commercially used for conducting electricity can be classed as conducting materials. When we study the

conducting properties of different type of materials, we find that, generally, these materials exhibit metallic bonding in their atomic structure. Moreover, when we go through the periodic table, we find that majority of conducting elements have a small number of electrons in their outermost shell. These small number of electrons present in the outermost shell are responsible for the formation of metallic bonds. Further, as explained earlier, a major property of these free electrons is that electrons from any of the atoms in the solid can travel right through the solid. Although there may be one or more electrons in the outermost shell of such metal atom, the solid is made up of millions of atoms and therefore the material may be imagined to consist of a large number of electrons all moving randomly with complete freedom through the solid. Each electron, when leaves the orbit of the parent atom, will cause the atom to become a positively charged ion. Hence, a solid metallic element consists of large number of positively charged metallic ions surrounded by a large number of free electrons. These electrons being able to wander freely through the solid is often referred as the 'electron gas'. The metallic bond can be thought of as the force of attraction between positive metal ions and the large number of electrons in the electron gas. As the valence electrons in metallic solids can carry the electric charge through the solid, these materials are good conductor of electricity. Other physical properties of these type of materials can also be described on the basis of their bonding.

So, it can be concluded that materials having small number of last orbit electrons, show metallic bonds, are good conductors, and hence called conducting materials.

### 1.7.2 Semiconducting Materials

Some materials have half filled last orbits. The majority of these materials exhibit covalent bonding in their structure. C, Si, Ge,

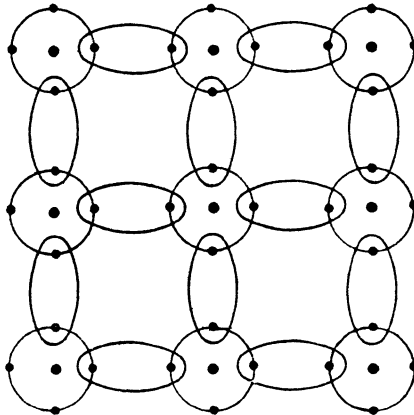


Fig. 1-5 Covalent bond of silicon atoms.



exhibit covalent bonding in their structure and these bonds are formed in the direction of electron charge cloud of electrons in the outermost shell.

Figure 1-5 shows the covalent bonds of silicon atoms. By having covalent bonding each atom acquires the configuration of inert gas.

These outer electrons are very tightly bonded to the atoms. It is very difficult to remove these electrons for conduction since a large amount of energy is required for removing the electrons.

However, in materials like Si and Ge, when thermal agitation is provided, the covalent bonds break to make available some free electrons.

Also we know that due to directional covalent bonding these materials exhibit crystalline structure. Silicon and germanium take up tetrahedral structure but these crystals are not perfect one. Some crystal imperfection like substitutional, vacancies, dislocation are present in their structure.

Due to these factors, Si and Ge exhibit some conductivity. Hence these materials are known as semiconductors. Semiconductors produced by thermal agitation alone are called intrinsic semiconductors. Since relatively few electrons are free at room temperature, the conductivity is small but rises exponentially with temperature.

Semiconductors produced by introduction of impurity atoms are called Extrinsic semiconductors. Due to crystalline structure of these materials, it is possible to add trivalent or pentavalent impurity atoms to their structure. For example, when a few antimony atoms having 5 valence electrons are introduced in the crystal structure of semiconductor material like silicon, which has 4 valence electrons, there will be a local excess of one electron for each covalent bond between silicon and antimony. Thus, each atom of antimony will provide an extra electron for conduction.

Therefore, in this way, we can say that materials having covalent bonding, and having crystal imperfection in their crystal structure like Si, Ge, exhibit semiconducting property.

### **1-7-3. Insulating Materials**

Any material which can prevent the flow charge through it when a difference of potential is applied across it is called an insulator. The reason, that a material exhibits insulating properties is that there are very small (almost negligible) number of free electrons in its structure and it is known that free electrons can only transmit charge through the structure of the materials.

The reason behind it is the non-existence of charge carriers or free electrons and therefore the majority of insulating materials

exhibit a very strong type of bonding in their structure. This bonding is known as 'ionic bonding'. We know that bond strength of the ionic bond is strongest among all three type of bonds. So electrons in ionic bond are tightly bonded. At room temperature number of free electrons in their structure is negligible. In the absence of free electrons these materials exhibit strong insulating properties.

This principle is not only applied to the various elements of the periodic table but also to the other compounds which are formed by ionic bonding, for example, number of carbon compounds (organic) which exhibit ionic bonding in their structure and very good insulating materials (For example PVC, polyethene, Teflon, other petroleum products).

Other materials which exhibit ionic bonding in their structure are also good insulating materials. In case of ionic bonding we know that electropositive and electronegative materials form strong ionic bonds by loosing and gaining the electrons respectively. After this process elements acquire the configuration of inert gas in their outermost orbit and their electronic configuration is very stable. It thus becomes very difficult to get free electron in their structure, which are essential for the flow of electric charge through the material. Hence, ionic bond solids exhibit strong insulating properties.

### 1.8. Magnetic Materials

According to the atomic theory all materials are made up of atoms. Each atom consists of a nucleus and a number of electrons revolving round the nucleus in different shells or energy levels. All the electrons around the nucleus do not revolve in the same shell but do so in different shells. Since current is the flow of electrons, the rotation of electrons around the nucleus is equivalent to circulating current. We know that when current flows through a coil it creates an m.m.f. Thus circulating electrons in a material also develops m.m.f. In most materials the direction of motion of electrons in the various shells is such that they develop m.m.f. in opposite directions cancelling each other. However, some *d*-block elements, *i.e.* metals (showing metallic bonds in their structure) have a number of unneutralized shells, which produce a resultant m.m.f. creating magnetic poles, called magnetic dipoles. For example, iron, nickle and cobalt have number of unneutralized orbits which produce magnetic dipoles.

In an unmagnetized material the dipoles are scattered randomly. In a magnetized material the dipoles line up parallel with the exciting m.m.f.

The property of a material by virtue of which it allows itself to be magnetized is called 'permeability'. For most of materials, except

those which are called magnetic materials, the value of permeability is constant and is the same as for free space. The permeability of free space is denoted by  $\mu_0$  and equals  $4\pi \times 10^{-7}$ . The permeability of air is same as that of free space.

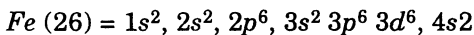
The number of possible electrons is restricted to two electrons in a subshell orbital. These two electrons will have equal energy, but their spin will be opposite.

Properties of magnetic materials are dependent on this “electron spin”. Generally speaking, a material with an even number of electrons has as many electrons spinning in one direction as in the other direction and the net effect is a magnetically insensitive structure.

But if we check the electronic structure of magnetic materials, we find that more electrons spin in one direction than in the opposite direction.

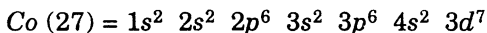
For example, consider the case of Iron (atomic number = 26) and cobalt (atomic number = 27).

The electronic configuration of iron is :



Iron has four unpaired electrons in 3d subshell. So, due to these unpaired electrons having spins in the same direction, Iron is a good magnetic material.

The electronic configuration of Cobalt is :



It has three unpaired electrons in 3d subshell, having spin in the same direction. Due to these unpaired electrons cobalt shows good magnetic properties.