

- (i) **Magnetic field, \mathbf{H} :** The magnetic field in which a material is kept is called *magnetizing field*. The strength (or intensity) of the magnetic field is denoted by H . The units of \mathbf{H} are ampere-turns per metre (A/m) in SI system. Magnetic field is produced by permanent magnets such as a horse shoe magnet and temporarily by electromagnets or superconductor-magnets.
- (ii) **Magnetization, \mathbf{M} :** *Magnetization* is defined as the magnetic moment per unit volume developed inside a solid and is denoted by \mathbf{M} . In SI system, magnetization is measured in amperes per metre (A/m). Since the magnetization is induced by the field, we may assume that \mathbf{M} is proportional to \mathbf{H} .

Thus,

$$\mathbf{M} \propto \mathbf{H}$$

or

$$\mathbf{M} = \chi \mathbf{H}$$

where χ is the proportionality constant and is known as *magnetic susceptibility*.

- (iii) **Magnetic Susceptibility, χ :** The *magnetic susceptibility* of a material is a measure of the ease with which the material can be magnetized.

Thus,

$$\chi = \frac{\mathbf{M}}{\mathbf{H}} \quad \dots(41.2)$$

In general, the vectors \mathbf{M} and \mathbf{H} can have different directions and χ is a tensor. However, in isotropic media, \mathbf{M} and \mathbf{H} point in the same direction and χ is a scalar quantity. Materials having high susceptibility are easily magnetized.

- (iv) **Magnetic Induction, \mathbf{B} :**

A magnetic field is schematically represented by lines of magnetic induction. It is described either by magnetic field strength \mathbf{H} or by the *magnetic induction* (or *magnetic flux density*), \mathbf{B} .

The lines of induction are collectively called *flux*. The number of field lines passing through a unit area of cross-section is called the *magnetic flux density*.

$$\mathbf{B} = \frac{\text{Magnetic flux}}{\text{area}} = \frac{\phi}{A} \quad \dots(41.3)$$

The quantity B is measured in weber per square metre (Wb/m^2) or tesla (T). The cgs unit for magnetic induction is the gauss (G).

$$1 G = 10^{-4} T$$

Relationship between \mathbf{B} and \mathbf{H} : When a material is kept in a magnetic field, two types of induction arise; one due to the magnetizing field, \mathbf{H} and the other as a consequence of the magnetization, \mathbf{M} of the material itself.

The magnetic induction, \mathbf{B} , produced inside the material is given by

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \quad \dots(41.4)$$

where μ_0 is known as the *permeability of the free space*. It is equal to $4\pi \times 10^{-7} H/m$. Using Eq. (41.1) in Eq. (41.4), we get

$$\mathbf{B} = \mu_0 (1 + \chi) \mathbf{H} \quad \dots(41.5)$$

or

$$\mathbf{B} = \mu \mathbf{H} \quad \dots(41.6)$$

where μ is called the *absolute permeability* of the medium.

Like χ , μ is in general a tensor. In isotropic medium, it is a scalar quantity. In case of free space, $\mathbf{M} = 0$ and Eq. (41.4) reduces to

$$\mathbf{B} = \mu_0 \mathbf{H} \quad \dots(41.7)$$

- (v) **Absolute Permeability, μ :** When a magnetic material is placed in a magnetic field, the magnetic field lines are redistributed and tend to pass more (or less in some cases) through the material. The *absolute permeability* of the material is a measure of the degree of which the field lines penetrate or permeate the material. **Absolute permeability** is defined as the ratio of the magnetic induction, B , in the medium to the magnetizing field, H .

$$\mu = \frac{B}{H} \quad \dots(41.8)$$

The unit of absolute permeability is henry per metre (H/m).

- (vi) **Relative Permeability, μ_r :** The relative permeability of a material is defined as the ratio of the absolute permeability of that material to the permeability of free space. That is,

$$\mu_r = \frac{\mu}{\mu_0} \quad \dots(41.9)$$

μ_r is only a number and has no units. Its value for air or vacuum is equal to unity. Thus,

$$\mu_r = 1$$

41.3 RELATION BETWEEN μ_r AND χ

Comparing Eq. (41.5) and Eq. (41.6), we find that

$$\mu = \mu_0(1 + \chi) \quad \dots(41.10)$$

Using Eq. (41.9) into the above equation, we obtain

$$\mu_r = (1 + \chi) \quad \dots(41.11)$$

Eq. (41.11) relates the permeability to susceptibility of the material.

Example 41.1: A magnetic material has a magnetization of 2300 A/m and produces a flux density of 0.00314 Wb/m². Calculate magnetizing force and relative permeability of the material.

Solution. Magnetizing force, $H = \frac{B}{\mu_0} - M = \frac{0.00314 \text{ Wb/m}^2}{12.57 \times 10^{-7} \text{ H/m}} - 2300 \text{ A/m} = 198 \text{ A/m}$.

Relative Permittivity, $\mu_r = \frac{B}{\mu_0 H} = \frac{0.00314 \text{ Wb/m}^2}{(12.57 \times 10^{-7} \text{ H/m})(198 \text{ A/m})} = 12.56$.

41.4 ORIGIN OF MAGNETIZATION-MAGNETIC MOMENT

The magnetic properties of solids arise due to electrons undergoing different motions in the atoms, which give rise to magnetic dipole moments. These magnetic dipole moments are responsible for the magnetic properties of materials. In general, the magnetic dipole moment of the atom arises from three sources:

- (i) **The orbital motion of electrons:** The atom of any material consists of a central nucleus and the electrons move around the nucleus in specific orbits. Each electron orbit is equivalent to a tiny current loop and behaves as an elementary magnet having a magnetic dipole moment. The total orbital magnetic moment of an atom is the sum of orbital magnetic moments of individual electrons.
- (ii) **The electron spin:** Each electron is spinning about an axis through itself and this spin also gives rise to a magnetic dipole moment.

- (iii) **The nuclear spin:** In addition to electronic contribution, nuclear spin also contributes to magnetic moment of atoms. The magnetic moment due to nuclear spin is not taken into account in understanding the magnetic properties of solids as the magnetic moment of the nucleus is very small, nearly 1/2000 of the magnetic moment of electron. We consider that the resulting magnetic moment of an atom is the sum of the orbital and spin magnetic moments of its electrons. The main contribution to atomic magnetic moment arises from the spin of unpaired valence electrons. Normally, the magnetic moments carried by atoms align in different directions to produce a net non-zero magnetic moment. When the substance is placed in a magnetic field, the atoms are aligned with their directions of magnetic moment along the direction of the magnetic field. Thus, the material is magnetized.

41.5 CLASSIFICATION OF MAGNETIC MATERIALS

Solids are classified into three groups based on the magnitude and sign of relative permeability, μ_r , exhibited by them, Diamagnetic materials ($\mu_r < 1$), Paramagnetic materials ($\mu_r > 1$), Ferromagnetic materials ($\mu_r \gg 1$). However, the solids can be divided into two broad groups, on the basis of *magnetic dipole moments*. The atoms of one group do not possess permanent magnetic dipole moment whereas atoms of the other group possess permanent magnetic dipole moment.

The materials consisting of atoms with zero magnetic dipole moment are called as **Diamagnetic materials**. Materials composed of atoms or molecules having permanent magnetic moment are classified into four categories depending on the interaction between the atomic magnetic dipoles. If the interaction between the atomic magnetic dipoles is negligible, the material is **paramagnetic**.

If the magnetic dipoles interact in such a way that they tend to orient in the same direction, the material is **ferromagnetic**. If neighbouring dipoles orient in opposite directions and if the dipoles are of equal magnitude, the material is **antiferromagnetic**. If the neighbouring dipoles are of different magnitude and orient antiparallel, the material is **ferrimagnetic**. The above four kinds of orientations of atomic dipoles are illustrated in Fig. 41.1.

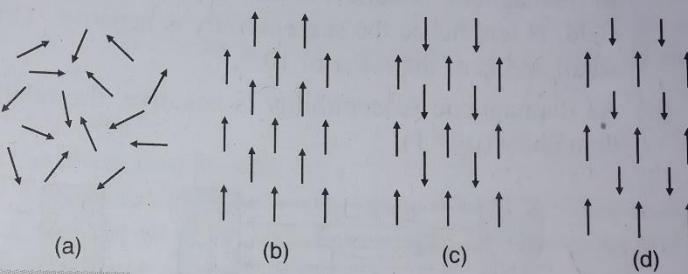


Fig. 41.1:

Schematic illustration of the orientation of spins in (a) paramagnetic, (b) ferromagnetic, (c) antiferromagnetic and (d) ferrimagnetic materials

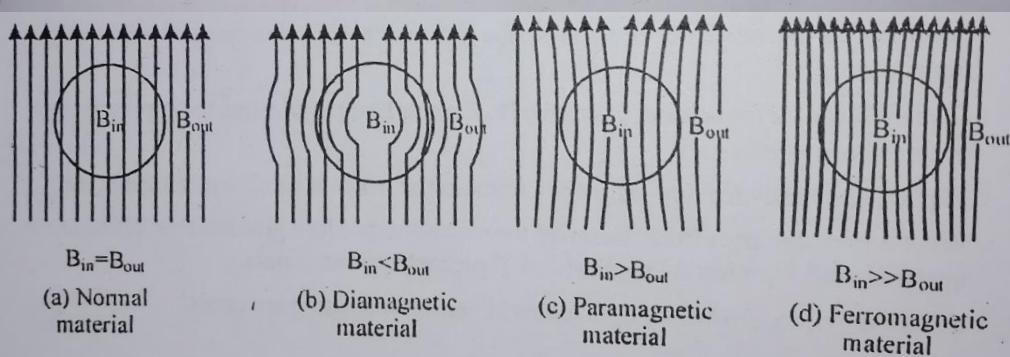


Figure 11.2 : Behaviour of magnetic materials in the presence of magnetic field

electric dipoles. The origin of magnetic dipoles is though very different from electric dipoles.

CLASSIFICATION OF MAGNETIC MATERIALS

The concept of magnetic dipoles plays a central role in the theory of magnetization. This is analogous to the role played by electric dipoles in the theory of polarization. Without going into the origin of magnetic dipoles, any magnetic material can be classified according to whether it has permanent magnetic dipoles or not. This means whether the constituent atoms, ions or molecules of the material has a magnetic dipole moment or not. Materials which lack permanent magnetic dipoles are called **diamagnetic**. Materials having permanent magnetic dipoles are divided into

- (a) Paramagnetic
- (b) Ferromagnetic
- (c) Antiferromagnetic
- (d) Ferrimagnetic



Fig. 6.1. One dimensional picture of arrangement of spins at $T=0$ (ground state) for para, ferro, antiferro and ferrimagnetic materials

If the interaction between the dipoles is ineffective then the material is paramagnetic otherwise it is Ferro, Antiferro or Ferrimagnetic depending upon the type of interaction between the spins. In absence of a magnetic field, in a paramagnet, the spins point in random directions and the net magnetization is zero. If the interaction favours alignment of dipoles in the same direction then the material is **ferromagnetic**. A ferromagnet has large net magnetization. In an antiferromagnet and ferrimagnet the neighbouring dipole line up so that they are antiparallel to each other. For an antiferromagnet the magnitude of the dipole moment of each dipole is the same and therefore the net magnetization

is zero. A ferrimagnet is made up of dipoles having different magnitudes so it has non-zero net magnetization

Magnitude of susceptibility	Temperature dependence of susceptibility	Examples
Small, Negative	Independent	Organic materials light elements.
Intermediate, Negative	When the temperature is below 20 K susceptibility varies with external magnetic field and with temperature also.	Alkali earths, Bismuth.
Large, Negative	Diamagnetism exists only below critical temperature ' T_c ' and susceptibility varies at this temperature ($T_c < 30$ K).	Superconducting materials like Niobium and its compounds, copper oxide superconducting materials, etc.

- Special remarks :**
1. Diamagnetic materials repel magnetic lines of force.
 2. There are no permanent dipoles; consequently magnetic effects are very small.
 3. Generally the value of diamagnetic susceptibility is independent of temperature and applied magnetic field strength.

Paramagnetic material

Definition

The number of orientations of orbital and spin magnetic moments be such that the vector sum of magnetic moments is not zero and there is a resultant magnetic moment in each atom even in the absence of applied field. If we apply the external magnetic field, there is an enormous magnetic moment along the field direction and the magnetic induction will increase. Thus paramagnetism is the phenomenon by which the orientations of magnetic moments are largely dependent on temperature and applied field. If the applied magnetic energy is greater than the thermal energy, the magnetic moment of the material is finite and large. These materials are used in Lasers and Masers where one can create the required energy levels for transition. Paramagnetic property of oxygen is used in the nuclear magnetic resonance imaging instrument which is used to diagnose the brain tumor or blood clot in the brain.

Magnitude of susceptibility	Temperature dependence of susceptibility	Examples
Small, Positive	Independent	Alkali metals and Transition metals.
Large, Positive	$\chi = \frac{C}{T - \theta}$ where C is equal to curie constant and θ is curie temperature. When $T < \theta$ paramagnetic substance converts into diamagnetic substance	Rare earths like chromium, yttrium, etc.,

- Special remarks :**
1. Paramagnetic materials attract magnetic lines of force.
 2. They possess permanent dipoles.
 3. The value of the paramagnetic susceptibility is independent of the applied magnetic field and depends greatly on temperature.

Spin alignment :



Ferromagnetic material

Definition : If a material acquires a relatively high magnetization in a weak field, then it is ferromagnetic. Further even in the absence of applied field, the magnetic moments are enormous. This is due to spontaneous magnetization. Ferromagnetism arises when the exchange energy is favourable for spin alignment.

Magnitude of Susceptibility : very large, positive.

Temperature dependence of susceptibility :

When temperature is greater than curie temperature ' θ ' then

$$\chi = \frac{C}{T - \theta} \quad (\text{paramagnetic region})$$

When temperature is less than ' θ ', the material is in ferromagnetic state and χ is very large due to spontaneous magnetization.

Examples : Fe, Ni, Co.

- Special remarks :**
1. Due to the large internal field, the permanent dipoles are strongly aligned in the same direction and consequently a large spontaneous magnetization results even in the absence of an applied field.
 2. They attract the lines of force very strongly.
 3. They exhibit magnetization even when the magnetizing field is removed. i.e. they exhibit magnetic hysteresis.
 4. During heating they lose their magnetization slowly.

Spin alignment :



Antiferromagnetic materials

Definition : This refers to spin alignment in an antiparallel manner in neighbouring magnetic ions resulting in zero net magnetization.

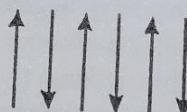
Magnitude of susceptibility : Small, Positive.

Temperature dependence of susceptibility : When $T > T_N$ (Neel temperature),

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

Examples : FeO (ferrous oxide), MnO (manganese oxide), Cr_2O_3 (chromium oxide) and salts of transition elements.

Spin alignment :



- Special remarks :**
1. The opposite alignment of adjacent magnetic moments in a solid is produced by an exchange interaction.
 2. Initially susceptibility increases slightly as the temperature increases and beyond Neel temperature the susceptibility decreases with the temperature.

Ferrimagnetic materials

Definition : It is a special case of antiferromagnetic in which antiparallel moments are of different magnitudes and a large magnetization arises.

Magnitude of susceptibility : Very large, positive.

Temperature dependence of susceptibility : At $T > T_N$, $\chi = \frac{C}{T \pm \theta}$

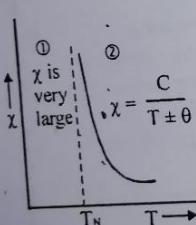
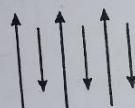
Examples : Ferrous Ferrite and Nickel ferrite

MAGNETIC PROPERTIES

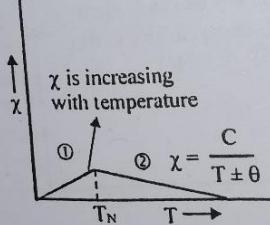
Special remarks : 1.

These are composed of two or more sets of different transition metal ions. There are different number of ions in each set. Due to that, unlike antiferromagnetics, there is a net large magnetization.

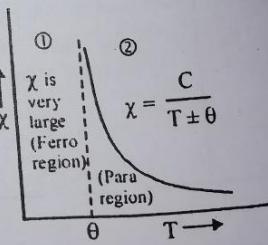
Spin alignment :



Ferrimagnetic material



Anti - Ferromagnetic material



Ferromagnetic material

Figure 11.3 : Variation of the susceptibility with temperature in different magnetic materials

In the other three magnetic behaviours, there is sufficient interaction between neighbouring dipoles. If the interaction leads to parallel alignment of neighbouring magnetic moments, ferromagnetic behaviour is exhibited. In case the result is antiparallel spin arrangement, antiferromagnetism (where the compensation of magnetic moments is complete and the net magnetization is zero) or ferrimagnetism (where the compensation is incomplete) arises. Fig. 6.12 indicates dipole arrangements for different magnetic behaviours. Table 6.1 summarizes features of different magnetic behaviour of materials.

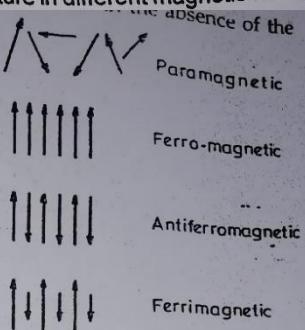


Fig. 6.12 Different magnetic behaviour of materials (arrangement of dipole moments or spins)

Table 6.1 Types of Magnetic Materials

Type	Susceptibility χ_m	χ_m vs T relation	Examples
(i) Diamagnetic	$\sim 10^{-6}$ (negative)	Independent	Atoms of solids having closed shells and some metals Au, Ge, etc.
(ii) Paramagnetic	$\sim 10^{-5}$ (positive)	$\chi_m = \frac{C}{T}$ Curie law or $\chi_m = \frac{C}{T - \theta}$ Curie-Weiss law	Atoms possessing odd number of electrons, ionic crystals, etc.
(iii) Ferromagnetic	Very large and positive	$(\chi_m \rightarrow \infty)$	Iron, cobalt, nickel, gadolinium.
(iv) Antiferromagnetic	Small and positive	χ_m decreases with temperature	Salts and oxides of transition metals, e.g. NiO, MnF ₂ .
(v) Ferrimagnetic	Large and positive	$\chi_m \rightarrow \infty$	Ferrites, e.g. Fe ₃ O ₄ .

11.4.2 Structure of ferrites

Ferrites are the modified structures of Iron with no carbon and are good examples of Ferrimagnetism in which the spins of adjacent ions in the presence of a magnetic field are in opposite senses and with different magnitudes. They are made from ceramic ferro magnetic compounds. Mechanically it has pure iron character. It has low tensile strength and it is a brittle, soft and non machinable one. In these all valence electrons are tied up by ionic bonding and these are bad conductors with high resistivity of 10^{11} ohm metre. Ferrites are manufactured by powder metallurgical process by mixing, compacting and then sintering at high temperatures followed by age hardening in magnetic fields. These are mainly used in transformer cores, television scanning coils, memory devices and high speed switches. The general formula is $X Fe_2 O_4$ where X may be a metal as Mg, Mn or Zn. These materials have low eddy current losses and low hysteresis losses.

Normally there are two types of structures present in the ferrites.

Regular spinel

In the regular spinel, each trivalent metal ion occupies an octahedral site (B) and each divalent ion occupies a tetrahedral site (A) of FCC oxygen lattice.

Example : $X^{2+} Fe_2^{3+} O_4$ where X is divalent metal ion such as Mn, Cu, Ni, Mg, etc.

Inverse spinel

In the inverse spinel, trivalent metal ions occupy all tetrahedral sites (A) and half of octahedral sites (B) and the rest of octahedral sites (B) are occupied by divalent metal ions.

Example : $Fe^{3+} (Fe^{2+}Fe^{3+}) O_4$ = Ferrous ferrite

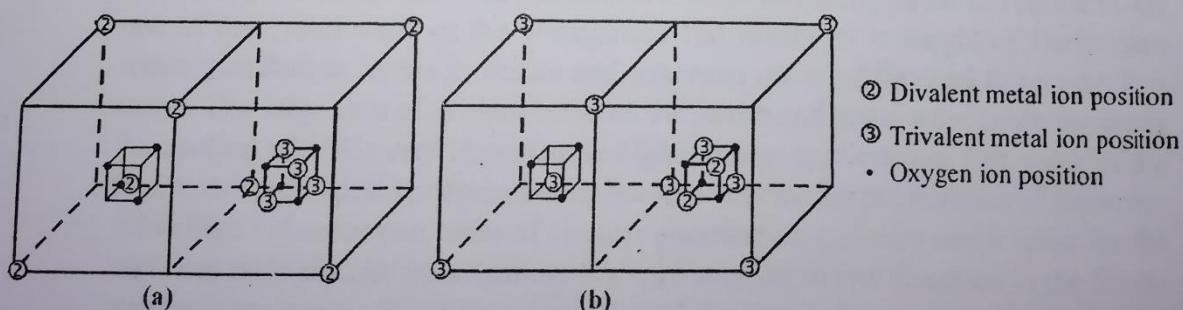


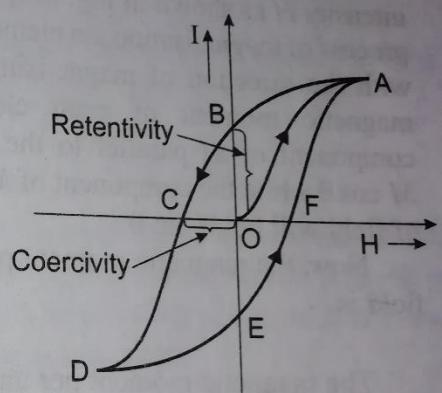
Figure 11.13 : (a) Regular spinel structure (b) Inverse spinel structure

11.4.3 Applications of ferrites

1. Ferrites are used to produce low frequency ultrasonic waves by magnetostriction principle.
2. Ferrite rods are used in radio receivers (particularly in medium wave coil) to increase the sensitivity and selectivity of receiver.
3. Ferrites are used as cores in audio and T.V. transformers
4. Since for ferrites eddy current loss and hysteresis loss are small at microwave frequencies, these are widely used in non-reciprocal microwave devices.

24.11 HYSTERESIS

Consider an unmagnetised ferromagnetic substance (say iron bar) in a magnetising field. The ferromagnetic materials show a relation between intensity of magnetization and strength of magnetic field. This property is called *hysteresis*. The literal meaning of hysteresis is *retardation* or lagging of an effect behind the cause of the effect. When the bar is slowly magnetised, the variation of intensity of magnetisation I is shown in Fig. (19).



magnetized. The hysteresis curves for

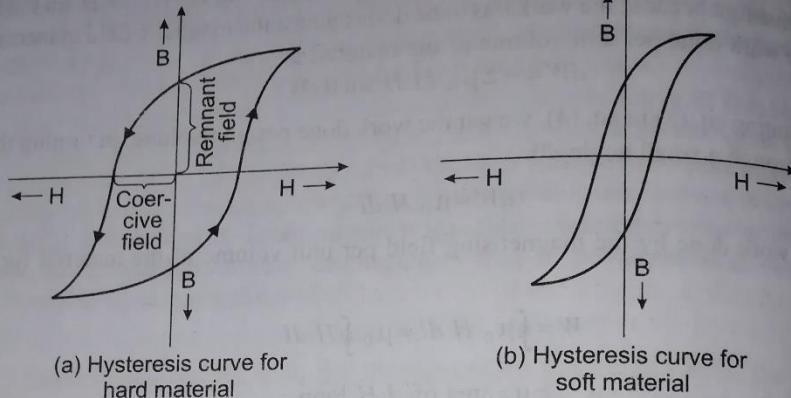


Fig. (21)

(A) Properties of Hard Magnetic Materials

Hard magnetic materials have the following properties.

- High remanent magnetisation: Its capacity to retain magnetism after the removal of magnetic field is quite high,
- High coercivity: it is difficult to demagnetize a material of high coercivity,
- High saturation flux density,
- Low initial permeability,
- High hysteresis energy loss,
- Low susceptibility, and
- Low eddy current loss.

Due to above properties, hard magnetic materials can neither be easily magnetized nor easily demagnetized.

Hard materials: Examples of hard magnetic materials are:

- Alnico alloy (Alloys of Al, Ni, Co, Cu and Fe)
- Tungsten steel alloy
- Chromium steel alloy
- Platinum cobalt alloy
- Invar

Uses: Hard magnetic materials are used in manufacture of permanent magnets. Permanent magnets are commercially very important. Most of them are manufactured from alloys of steel with tungsten and chromium. Magnet for toys and measuring meters are made of carbon steel because of low cost.

(B) Properties of Soft Magnetic Materials

Soft materials have the following properties:

- Low remanent magnetisation,

- (ii) Low coercivity,
- (iii) Low hysteresis loss,
- (iv) High permeability,
- (v) High susceptibility.

Therefore, soft materials are easily magnetized and easily demagnetized.

Soft materials: Examples of soft magnetic materials are :

- (a) Permalloy (alloy of Fe and Ni)
- (b) Silicon (Iron alloy)
- (c) Commercial iron
- (d) Mumetal (Alloy of Ni, Cu, Cr and Fe)
- (e) Amorphous ferrous alloys (Alloys of Fe, Si and B)

Uses: The most important use of soft magnetic metals is in the core of transformers and especially the ones employed in power generations. Iron-Nickel alloys are used for audio frequency applications. Iron-silicon alloys are used for low frequency and high power applications. Following are few applications.

24.14 USES OF HYSTERESIS CURVE TO SELECT THE MATERIAL

The properties of hysteresis curve, i.e., saturation, retentivity, coercivity and hysteresis loss help us to choose the material for specific purpose.

(i) **Permanent magnets.** The permanent magnet material must retain large residual magnetism. We want that in permanent magnet its magnetism should be permanent and not easily destroyed. Thus, it must have large coercivity. So, a permanent magnet should have both large retentivity and large coercivity. The best suited materials are cobalt, steel, alnico, ticonol, etc. The very suitable alloy of highest coercivity is vicalloy (vanadium + iron + cobalt). Permanent magnets are used in galvanometers, voltmeters, ammeters, microphones, loudspeakers, telephones, etc.

(ii) **An electromagnet core.** The electromagnet core material should have maximum flux density B even with small fields H , low hysteresis loss and high initial permeability. Annealed soft iron has these properties.

(iii) **Transformer cores, Dynamo core, chokes, Telephone diaphragms, etc.** The core material should have high initial permeability, low hysteresis loss and high specific resistance to reduce eddy currents. Soft iron is the best suited material.

16.7 LANGEVIN'S CLASSICAL THEORY OF DIAMAGNETISM

As we know that the diamagnetism is the occurrence of negative susceptibility and the magnetization M in this case is antiparallel to the field (eq. 3). There is no electrical counterpart to the negative susceptibility, although it is vaguely analogous to the depolarization field (section 14.5). The negative susceptibility arises from Lenz's law which states that when the flux in an electrical circuit is changed, an induced current is set up in such a direction as to oppose the flux change. For the following discussion, a circuit will mean the circulating electron in an atom, ion or molecule at a lattice site. Let us consider the Bohr model of atom, i.e. consider an electron which revolves round a central nucleus as shown in Fig. 16.9. If m is the mass of the electron, $-e$ is the charge of the electron and r is the radius of the orbit then in the absence of an external field the centripetal force acting on the electron due to the nucleus is given by

$$F_0 = \frac{mv^2}{r} = m\omega_0^2 r \quad (24)$$

where $v = \omega_0 r$. When a magnetic field is applied along the z -axis (perpendicular to the xy -plane), an additional force F_L equal to the Lorentz force starts acting on the electron in a direction away from the centre. The Lorentz force is given by

$$F_L = -e(v \times B) = -eBr\omega \quad (25)$$

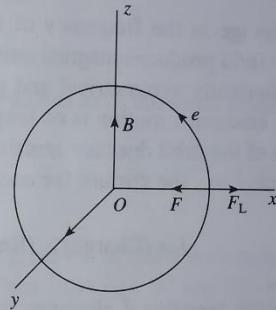


Fig. 16.9 Motion of an electron in xy -plane

where the magnetic field B is perpendicular to r . Because of the change in the net force on the electron, there is a change in the angular frequency from ω_0 to ω . The resulting equation can be written as

$$F_0 - eBr\omega = m\omega^2r \quad (26)$$

Substituting F_0 from eq. 24 into eq. 26 and solving for ω , we obtain

$$\omega^2 + \frac{eB}{m}\omega - \omega_0^2 = 0$$

so that

$$\omega = \pm \left[\left(\frac{eB}{2m} \right)^2 + \omega_0^2 \right]^{1/2} - \frac{eB}{2m}$$

If $\omega_0 \gg \left(\frac{eB}{2m} \right)$ then $\left(\frac{eB}{2m} \right)^2$ term can be neglected, therefore,

$$\omega = \pm \omega_0 - \frac{eB}{2m} = \pm \omega_0 - \omega_L \quad (27)$$

where the change of frequency $\omega_L = eB/(2m)$ is called the precessional frequency or Larmour frequency. The (\pm) sign on ω_0 implies that those electrons whose orbital moments are parallel to the field are slowed down by ω_L . In this case, $\omega = \omega_0 - \omega_L$. Similarly those electrons whose moments are antiparallel to the field are speeded up by the same amount. In this case, $\omega = -\omega_0 - \omega_L$.

The change in the frequency of the electronic motion as a result of the application of the magnetic field produces magnetization. Actually, in the absence of the field the electron motion being spherically symmetrical and produces no net current or flux. On the other hand, in the field, the electron's motion is no longer spherically symmetric but precesses about the field (i.e. the plane of the orbit does not remain stationary) and produces a net current I . Due to the change in frequency ω_L , the current for each electron can be written as

$$I = (\text{Charge}) \times (\text{Revolution per unit time}) = -\frac{e\omega_L}{2\pi} = -\frac{e^2 B}{4\pi m} \quad (28)$$

If each atom contains Z electrons then the current becomes

$$I = -\frac{Ze^2 B}{4\pi m} \quad (29)$$

Making use of eq. 9, the magnetic moment could be written as

$$\mu_m = -\frac{Ze^2 B}{4\pi m} \pi \bar{\rho}^2 \quad (30)$$

where $\bar{\rho}^2$ is the mean square radius of the projection of the orbit on a plane perpendicular to the field axis (Fig. 16.10). As the field is acting parallel to the z-axis, therefore

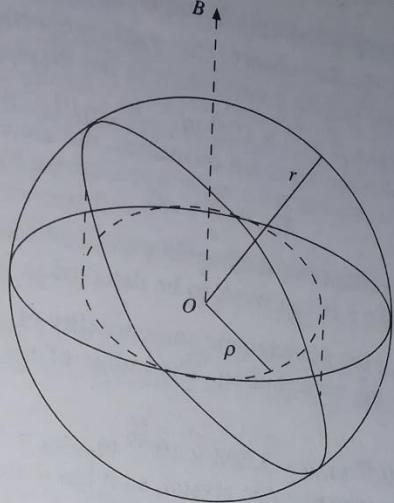


Fig. 16.10 Great circle and projection of inclined circular orbits in a plane perpendicular to the field

$$\bar{\rho}^2 = \bar{x}^2 + \bar{y}^2$$

The mean square distance (average radius) of the electron from the nucleus is

$$\bar{r}^2 = \bar{x}^2 + \bar{y}^2 + \bar{z}^2$$

Now, for spherically symmetric charge distribution, we have

$$\bar{x}^2 = \bar{y}^2 = \bar{z}^2$$

Here, average is used because all the electrons in an atom do not have the same effective radii, so that

$$\bar{\rho}^2 = \frac{2}{3}\bar{r}^2 \quad (33)$$

This result expresses the fact that the projected area of the great circle tilted with respect to the equatorial plane is less than πr^2 as shown in Fig. 16.10. Thus from eqs. 30 and 33, we obtain

$$\mu_m = -\frac{Ze^2 B \pi \frac{2}{3} \bar{r}^2}{4\pi m} = -\frac{Ze^2 B \bar{r}^2}{6m} \quad (34)$$

If N is the number of atoms per unit volume, then the magnetization M is given by $M = N\mu_m$ (also making use of the fact that $B = \mu_0 H$), the diamagnetic susceptibility per unit volume is

$$\chi_{dia} = \frac{M}{H} = -\frac{\mu_0 Ze^2 N \bar{r}^2}{6m} \quad (35)$$

This is the classical Langevin equation for diamagnetism. From eq. 35, it is clear that the

Langevin's theory of paramagnetism:

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sumed to be negligible. In the presence of a magnetic induction \mathbf{B} , these dipoles tend to orient themselves in the direction of the field in order to minimize their energy. The thermal energy at ordinary temperatures, however, resists such an alignment of dipoles. In thermal equilibrium, the dipoles orient themselves at an angle θ with the direction of the applied field as shown in Fig. 8.1. The potential energy of each dipole in this position is given by

$$E = -\mu \cdot \mathbf{B} = -\mu B \cos \theta$$

Using Maxwell-Boltzmann distribution law, the number of magnetic dipoles having this particular orientation is proportional to

$$\exp\left(-\frac{E}{kT}\right) \quad \text{or} \quad \exp\left(\frac{\mu B \cos \theta}{kT}\right)$$

Also, according to statistical mechanics, the probability for a magnetic dipole to make an angle between θ and $\theta + d\theta$ with the magnetic field, or the number of dipoles, dn , having axes within the solid angle $d\omega$ lying between two hollow cones of semiangles θ and $\theta + d\theta$ (Fig. 8.1) is given by

$$\begin{aligned} dn &\propto \exp\left(\frac{\mu B \cos \theta}{kT}\right) d\omega \quad (i) \\ &= k \exp\left(\frac{\mu B \cos \theta}{kT}\right) 2\pi \sin \theta d\theta \quad (ii) \end{aligned} \quad (8.29)$$

where k is a constant. Each one of these dipoles contributes a component of magnetic moment $\mu \cos \theta$ to the magnetization, whereas the components perpendicular to the field direction cancel each other. Hence the average

The total number of dipoles N lying within a unit volume and having potential energy W is given by

$$N = \int_0^\pi dN = A \int_0^\pi e^{\beta \cos \theta} \sin \theta d\theta \quad \dots(41.20)$$

If a magnetic dipole μ_m inclined at an angle θ to the applied magnetic field, the component of its moment in the field direction is $\mu_m \cos \theta$. The magnetic moment contributed by dN dipoles is given by $dN \cdot \mu_m \cos \theta$.

The total magnetic moment due to N molecules per m^3 is given by

$$p_m = \int_0^\pi dN \mu_m \cos \theta$$

$$\text{But } p_m \text{ is the same as magnetization. Therefore, } M = \int_0^\pi dN \mu_m \cos \theta.$$

or

$$M = A \mu_m \int_0^\pi e^{\beta \cos \theta} \cos \theta \sin \theta d\theta$$

$$\text{From Eq. (41.20), we have } A = \frac{N}{\int_0^\pi e^{\beta \cos \theta} \sin \theta d\theta}$$

$$M = N \mu_m \frac{\int_0^\pi e^{\beta \cos \theta} \cos \theta \sin \theta d\theta}{\int_0^\pi e^{\beta \cos \theta} \sin \theta d\theta}$$

Setting $\cos \theta = y$, we get $dy = -\sin \theta d\theta$. We can write the above equation as

$$\begin{aligned} M &= N \mu_m \frac{\int_{-1}^1 e^{\beta y} y (-dy)}{\int_{-1}^1 e^{\beta y} (-dy)} = N \mu_m \frac{\left[\frac{e^{\beta y}}{\beta} \cdot y \right]_{-1}^1 - \left[\frac{e^{\beta y}}{\beta^2} \right]_{-1}^1}{\left[\frac{e^{\beta y}}{\beta} \right]_{-1}^1} \\ &= N \mu_m \frac{\left[-\frac{e^{-\beta}}{\beta} - \frac{e^\beta}{\beta} \right] - \left[-\frac{e^{-\beta}}{\beta^2} - \frac{e^\beta}{\beta^2} \right]}{\left[\frac{e^{-\beta}}{\beta} - \frac{e^\beta}{\beta} \right]} = N \mu_m \frac{-\frac{2}{\beta} \left[\left(\frac{e^\beta + e^{-\beta}}{2} \right) - \left(\frac{e^\beta - e^{-\beta}}{2\beta} \right) \right]}{-\frac{2}{\beta} \left(\frac{e^\beta - e^{-\beta}}{2} \right)} \\ &= N \mu_m \frac{\cosh \beta - \frac{1}{\beta} \sinh \beta}{\sinh \beta} = N \mu_m \left(\coth \beta - \frac{1}{\beta} \right) \end{aligned} \quad \dots(41.21)$$

$$M = N \mu_m L(\beta) \quad \dots(41.22)$$

The function $L(\beta) = \left(\coth \beta - \frac{1}{\beta} \right)$ is known as the **Langevin function**.

Then

$$\begin{aligned} |L(\beta)|_{\beta \rightarrow \infty} &= \left| \left(\cosh \beta - \frac{1}{\beta} \right) \right|_{\beta \rightarrow \infty} = \left| \frac{e^\beta + e^{-\beta}}{e^\beta - e^{-\beta}} - \frac{1}{\beta} \right|_{\beta \rightarrow \infty} \\ &= \left| \frac{1 + e^{-2\beta}}{1 - e^{-2\beta}} - \frac{1}{\beta} \right|_{\beta \rightarrow \infty} = 1 \end{aligned}$$

$$M_s = N\mu_m$$

where M_s denotes the saturation value of magnetization.

It will be attained either when the applied field \mathbf{B} is very large or the temperature is very low. It corresponds to the condition where all the dipoles are completely aligned in the field direction.

Case(ii): $\mu_m \beta \ll kT$ and $\beta \ll 1$.

The magnetic moment μ_m of an atom has a magnitude of the order of 10^{-23} J/T. At moderate fields of the order of 1 Tesla, $\mu_m B = 10^{-23}$ J. The factor kT is about 4×10^{-21} J at room temperature. It follows that $\mu_m \beta \ll kT$ for not very strong magnetic fields.

For values of $\beta \ll 1$, the Langevin function is given by

$$\therefore L(\beta) = \left[\frac{1}{\beta} + \frac{\beta}{3} - \frac{\beta^3}{45} + \frac{2\beta^5}{945} + \dots \right] - \frac{1}{\beta} \approx \frac{1}{\beta} + \frac{\beta}{3} - \frac{1}{\beta} = \frac{\beta}{3}.$$

$$\therefore L(\beta) = \frac{\mu_m \beta}{3kT}$$

Substituting the above value of $L(\beta)$ into Eq. (41.22), we obtain

$$\begin{aligned} M &= \frac{N\mu_m \beta}{3} = \frac{N\mu_m^2 B}{3kT} \\ \text{or} \quad M &= \frac{N\mu_0 \mu_m^2 H}{3kT} \end{aligned} \quad \dots(41.23)$$

$$\therefore \chi_{\text{para}}^{\text{orb}} = \frac{M}{H} = \frac{N\mu_0 \mu_m^2}{3kT} = \frac{C}{T} \quad \dots(41.24)$$

where the Curie constant C is given by

$$C = \frac{N\mu_0 \mu_m^2}{3k} \quad \dots(41.25)$$

Eq. (41.24) is the Curie's law.

The Curie constant of paramagnetic FeCl_3 is 3.7×10^{-3} at 27°C . What

XII. WEISS THEORY OF PARAMAGNETISM

Langevin theory failed to explain the complicated type of dependence of susceptibility upon temperature exhibited by paramagnetic substances. Example: Compressed and cooled gases, solid salts, crystals, etc. Furthermore, this theory does not throw light on the intimate relationship between para and ferromagnetism.

Weiss introduced the concept of *internal molecular field* in order to explain the complicated type of dependence of susceptibility. In a real gas, the molecules are mutually influenced by their magnetic moments and consequently, there should exist within the gas a molecular field. This field produced at any point by all the neighbouring molecules, is proportional to and acting in the same sense as the intensity of magnetisation. Let this internal molecular field be H_i .

Now

$$H_i = \lambda M$$

where λ is *molecular field coefficient*. Therefore net effective field should be

$$H_e = H + H_i$$

$$\text{Equation (9.37a) is } M = M_s(a/3)$$

$$= \mu_m N \left[\frac{\mu_m B_e}{3k_B T} \right]$$

$$= \mu_m N \left[\frac{\mu_m \mu_0 H_e}{3k_B T} \right]$$

$$M = \frac{\mu_m^2 N \mu_0}{3k_B T} [(H + \lambda M)]$$

Introducing the value of M from equation (9.37a) on the right-hand side of the above equation, one gets

$$M = \frac{\mu_m^2 N \mu_0}{3k_B T} \left[H + \frac{\mu_m^2 N H \lambda}{3k_B T} \right]$$

$$M = \frac{\mu_m^2 NH\mu_0}{3k_B T} \left[1 + \frac{\mu_m^2 N\lambda}{3k_B T} \right]$$

$$M = \frac{N\mu_0\mu_m^2 H / 3k_B T}{\left[1 - \frac{\mu_m^2 N\lambda}{3k_B T} \right]}$$

$$M = \frac{N\mu_0\mu_m^2 H}{3k_B T \left[1 - \frac{\mu_m^2 N\lambda}{3k_B T} \right]} = \frac{N\mu_0\mu_m^2 H}{3k_B T \left[1 - \frac{\mu_m^2 N\lambda}{3k_B T} \right]}$$

$$\chi = \frac{M}{H} = \frac{N\mu_0\mu_m^2}{3k_B [T - (\mu_m^2 N\lambda / 3k_B)]} = \frac{N\mu_0\mu_m^2}{3k_B (T - \theta_c)} \quad (9.42)$$

where $\theta_c = (\mu_m^2 N\lambda / 3k_B)$ is called *paramagnetic curie point*. Equation (9.42) is called *Curie-Weiss law*. This strange conclusion of Weiss law finalises that below paramagnetic curie temperature ($T < \theta_c$), susceptibility becomes negative. However, it should be noted that for most of the paramagnetic substances, curie temperature is quite low so that a situation for which $T < \theta_c$ is rare.

16.13 THE WEISS MOLECULAR (EXCHANGE) FIELD

In order to explain the spontaneous magnetization of a ferromagnetic material, Weiss (1907) assumed that there exists an internal molecular field (also called exchange field H_{ex}) acting on a given dipole and is given by

$$H_{ex} = H + \lambda M \quad (54)$$

where λ is called Weiss constant (it is independent of temperature) and H is applied field. In a ferromagnet the Curie law holds for exchange field as well. Therefore,

$$\frac{M}{H_{ex}} = \frac{C}{T} \quad (55)$$

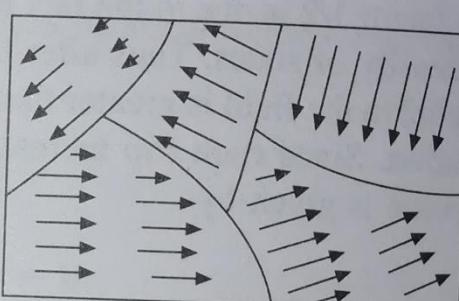


Fig. 16.14 Ferromagnetic domain

Simplifying the eqs. 54 and 55, we have

$$M = \frac{CH}{T - C\lambda} \quad (56)$$

Therefore, the ferromagnetic susceptibility becomes,

$$\chi = \frac{M}{H} = \frac{C}{T - C\lambda} = \frac{C}{T - T_c} \quad (57)$$

where $T_c = C\lambda$ is called the Curie temperature and the eq. 57 is known as Curie-Weiss law. The corresponding variation of susceptibility is

8.5.2 Nature and Origin of Weiss Molecular Field : Exchange Interactions

The Weiss theory of ferromagnetism is based on the concept of ferromagnetic domains which are spontaneously magnetized due to the presence of an internal molecular field called the *Weiss field* or the *exchange field*, B_E . The theory, however, does not explain the origin and nature of this field. The Weiss field cannot be simply due to magnetic dipole-dipole interaction between the neighbouring dipoles as this would generate fields of the order of 10^3 G only whereas the actual field strengths are observed to be quite high. For example, the Weiss field for iron is of the order of 10^7 G. It was Heisenberg who first proposed in 1928 that the Weiss field was the consequence of the quantum-mechanical exchange interaction between the atoms. This interaction arises due to the Pauli's exclusion principle according to which any change in the relative orientation of the two spins would disturb

Magnetism in Solids

the spatial distribution of charge, thus producing interaction between the two atoms. Apparently, the strength of exchange interaction between the adjacent atoms depends on the extent of overlap of their wave functions as well as the relative orientation of the electron spins but not on the spin magnetic moments. Thus this is an electrostatic and non-magnetic type of interaction.

Using Heitler-London theory of chemical bonding, it can be shown that the total energy of a system of two atoms contains an exchange energy term given by

$$U_{ij} = -2J_e \mathbf{S}_i \cdot \mathbf{S}_j \quad (8.67)$$

where \mathbf{S}_i and \mathbf{S}_j represent the spins of the two atoms and J_e is the exchange integral which is assumed to be the same for any pair of atoms. Its value depends on the overlap of the charge distributions of the two atoms, i.e., on the interatomic distance. In general, J_e is positive for large interatomic distances and negative for smaller ones. The expression (8.67) is known as the *Heisenberg model* of exchange energy. It also follows from (8.67) that if J_e is positive, the parallel arrangement of spins exhibits lower energy and hence is more stable as compared to the antiparallel arrangement, thereby producing magnetization. In a similar way, it can be concluded that the negative value of J_e does not favour magnetism.

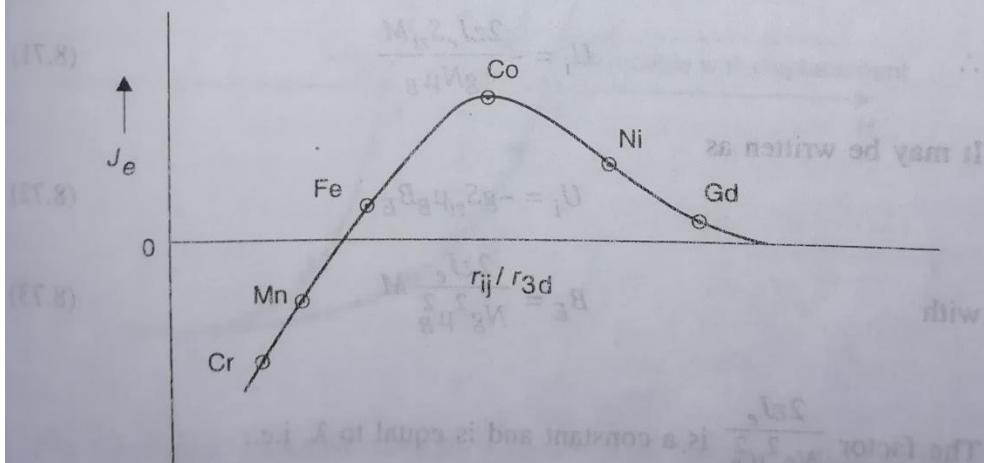


Fig. 8.5. Plot of exchange integral, J_e versus ratio of interatomic separation to the radius of the 3d orbit, r_{ij}/r_{3d}

The exchange integral for iron group of atoms is found to be positive inspite of the fact that the interatomic distance for this group is not large. This follows from the observations of Bathe and Slater which indicate that J_e is positive if the ratio r_{ij}/r_{3d} is greater than 3 but is not much larger than 3, r_{ij} being the distance between the atoms i and j and r_{3d} is the radius of the unfilled

(from section 16.14) that well below T_c , the magnetization is almost uniform and have high degree of order in such a magnetic system, the entropy term from the free energy expression may be neglected. Thus, the minimum free energy means minimum total internal energy E of the system. The knowledge of which should be sufficient to understand of existence of domains.

Landau and Lifshitz have shown that the domain structure is a natural consequence of various energies contributing towards the total energy of a ferromagnet. They are: the exchange energy, the magnetic field energy and the anisotropy energy.

1. The Exchange Energy

From section 16.15, we know that the exchange energy, E_{ex} is minimum when the spins are parallel. It is because of this energy, the spontaneous magnetization occurs in such materials. This energy establishes the existence of a single domain in a specimen of ferromagnetic material (Fig. 16.22a). The exchange energy favours an indefinitely large domain (the whole sample), since it is minimum when all spins are parallel.

2. The Magnetic Field Energy

In this case, we shall see that by dividing a crystal into two domains, the magnetic energy can be reduced to minimum or even to zero for certain domain structures (Fig. 16.22). Because of the free magnetic poles at the ends of the specimen, having a single domain (Fig. 16.22a) will have highest magnetic energy $(1/8\pi) \int B^2 dV$. However, this energy can be reduced to roughly half by dividing the crystal into two domains magnetized in opposite directions as in Fig. 16.22b. Similarly, dividing the crystal into N domains (Fig. 16.22c), reduces the magnetic energy by $1/N$ or more accurately by $0.8525 M_s^2 / N$. However, since certain amount of energy is required to create a domain boundary wall, this subdivision process can be continued until the energy required to create an additional interface, the domain (Bloch) wall, between the domains is greater than the reduction in magnetic energy. In fact, for a given size of the sample, the number and the arrangement of domains present is a compromise between these two energy terms. Taking this into account, the domain arrangements shown in Figs. 16.22d and 22e will have zero magnetic field energy. This is achieved by introducing the triangular prism domains near the end faces of the crystal; such domains are called closure domains. Here, it is to be noted that the boundary walls of the closure domains make equal angles (i.e. 45°) with the direction of magnetization each due to closure domains themselves and vertical domains. This means that the

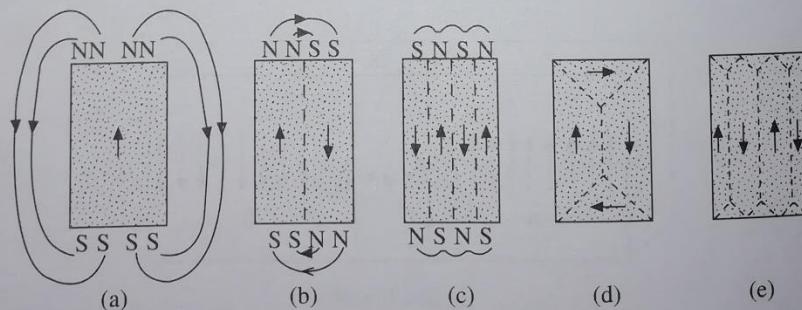


Fig. 16.22 The origin of domains

Magnetostatic Energy

The interaction energy which makes the adjacent dipoles align themselves is the exchange energy or the magnetic field energy. Let us suppose in Fig. 9.41 (a), the exchange energy has established a single domain in a specimen of ferromagnetic material. Because of the free magnetic poles formed on the surface of the crystal, this configuration will have high magnetic energy $(1/8\pi) \int H^2 dv$. In fact this is the energy required in assembling the atomic magnets into a single domain and this work done is stored as potential energy in the field outside. In Fig. 9.41 (b), the magnetic energy has been reduced by one half as a result of dividing the crystal into two domains magnetised in opposite directions. The subdivision can be continued until the reduction in magnetic energy is less than the increase in energy to form another domain and its boundary called *Bloch wall*. A domain structure as in Fig. 9.41 (c) and 9.41 (d) has zero magnetic energy. Here the boundaries of triangular prism domains as *closure domains* near the end faces of the crystal, make equal angles of 45° with the magnetisation direction. Hence the normal component of the magnetisation in crossing such a wall is continuous, i.e., there are no free poles and there is no field energy. The energy required to produce a closure domain is essentially determined by the anisotropy of the crystal, i.e., by the fact that ferromagnetic materials have 'easy' and 'hard' directions of magnetisation. Summarising the ideas discussed above we may say that domain structure will depend to a large extent on the shape and size of the crystal under consideration. The size of the domains for a particular domain structure may also be obtained from the principle of minimum energy. The volume of the domains may vary between say, 10^{-2} to 10^{-6} cm^3 .

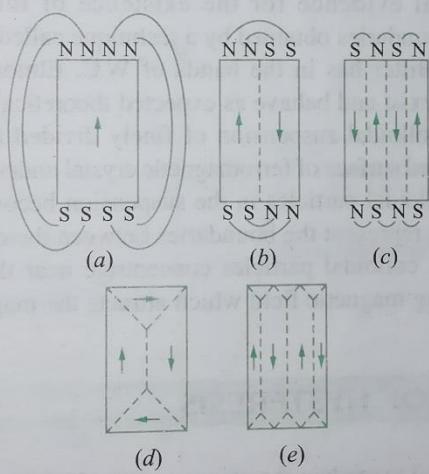


Fig. 9.41 The origin of domains

not happen. We know from thermodynamics that every solid structure will take up that configuration for which the free energy ($E - TS$) is a minimum. Due to the high degree of order in magnetic systems we can neglect the entropy term and concentrate only on the internal energy term. The total internal energy of the domain structure in a ferromagnetic material is made up from the following contributions:

- (i) Magnetostatic energy or the magnetic field energy or the exchange energy.
- (ii) Crystalline energy or the anisotropy energy.
- (iii) Domain wall energy or the Bloch wall energy.
- (iv) Magnetostriction energy.

Anisotropy Energy

It is found that the ferromagnetic crystals have easy and hard directions of magnetisation, i.e., higher fields are required to magnetise a crystal in a particular direction than others. For example, in bcc iron the easy direction is [1 0 0], the medium direction is [1 1 0] and the hard direction is [1 1 1]. In nickel easy direction is [1 1 1], the medium direction is [1 1 0] and the hard direction is [1 0 0].

The difference between the easy and hard directions is, that for producing the same saturation magnetisation, stronger fields are required in the hard direction than in the easy direction. The excess of energy required to magnetise a specimen in a particular direction over that required to magnetise it along the easy direction is called the *crystalline anisotropy energy*.

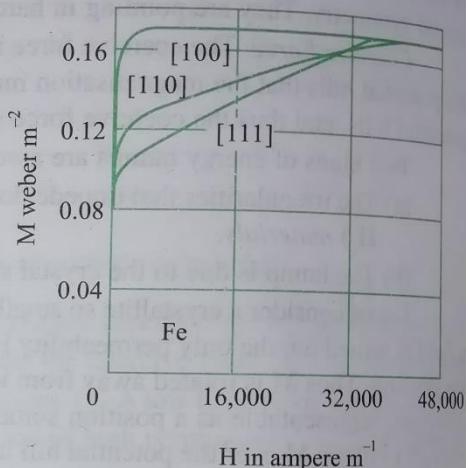


Fig. 9.40 (b) Magnetisation curves for a single crystal of iron

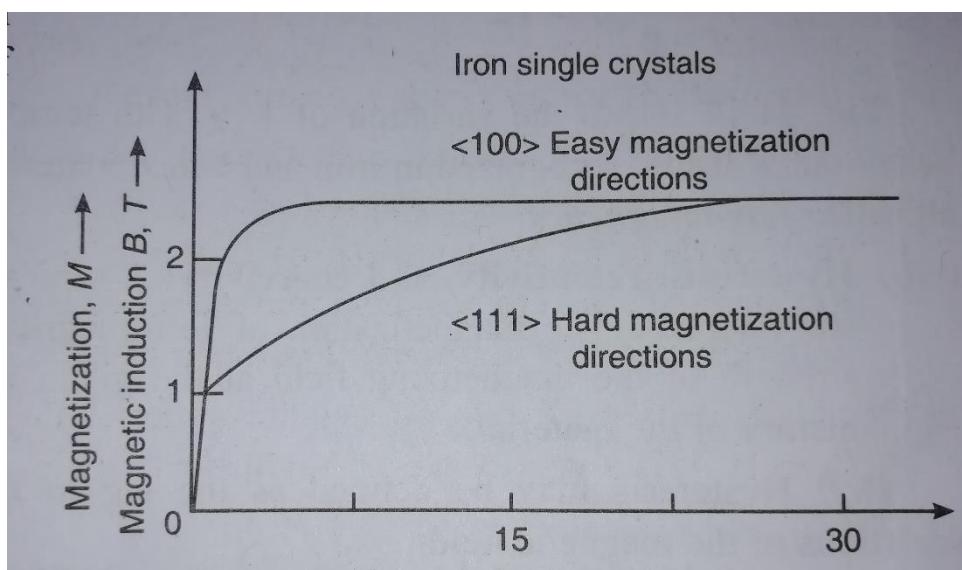


Fig. 41.12:

Magnetization versus applied field for different crystallographic directions in an iron crystal.

Bloch Wall or the Domain Wall Energy

The term Bloch wall denotes the transition layer which separates adjacent domains magnetised in different directions. The essential idea of Bloch wall is that the spin direction in going from one domain to another does not change abruptly in one plane but gradually as indicated in Fig. 9.42 over many atomic planes. The domain walls are called Bloch walls. The reason for the gradual nature of change is the fact that for a given total change of spin direction the exchange energy is lower when the change is distributed over many spins than when the change occurs abruptly. This implies that the Bloch wall is thick.

But the anisotropy energy will be small if the spins change abruptly *i.e.*, the Bloch wall is thin. So the thickness of the Bloch wall is a compromise between the two. Usually the Bloch walls are about 200 to 300 lattice constant thickness.

Magnetostrictive Energy

When a specimen is magnetised it is found that it suffers a change of dimensions and this phenomenon is known as magnetostriction. This deformation is different along different crystal directions. So if the domains are magnetised in different directions they will either expand or shrink. This means that work must be done against the elastic restoring forces. The work done by the magnetic field against these elastic restoring forces is the energy due to *magnetostriction* or the *magneto-elastic energy*. If the lattice is not strained the magneto-elastic energy is zero. But usually the lattice is strained along the different directions of magnetisation of the domains.

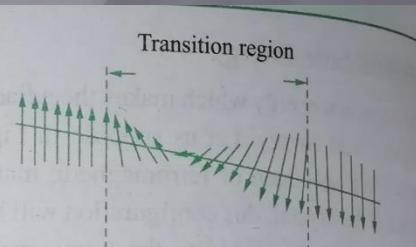


Fig. 9.42 Schematic diagram of the transition region separating ferromagnetic domains in a 180° Bloch wall

Applications of Magnetic Materials:

41.16 MAGNETIC DEVICES

(i) **Transformers Cores:** Transformers consist of a number of parts. The core makes up the bulk of a transformer. It is a piece of high permeability magnetic material used to

confine and guide magnetic fields in electrical devices. The composition of a transformer core depends on voltage, current, and frequency. It is usually made of ferromagnetic metal such as iron, or ferrites. The high permeability, relative to the surrounding air, causes the magnetic field lines to be concentrated in the core material. The presence of the core can increase the magnetic field of a coil by a factor of several thousand over what it would be without the core. A range of cores exist, such as steel laminated, solid, toroidal, pot and planar cores, etc. (Fig. 41.24).

Steel Laminated Cores: Steel laminated cores are used for transmitting voltage at the audio frequency level. Laminated core with several steel laminations, protected by an insulator material between layers, confines the eddy currents and lessens magnetizing effects. Although thin laminations are harder to manufacture and are more expensive, they are effective in high frequency transformers.

Several designs of steel laminated transformers are available, each offering its own advantages. An E shaped core is affordable to manufacture, but tends to exhibit more energy loss. A C type core offers reduced resistance because the metal grains run parallel to the energy flux.

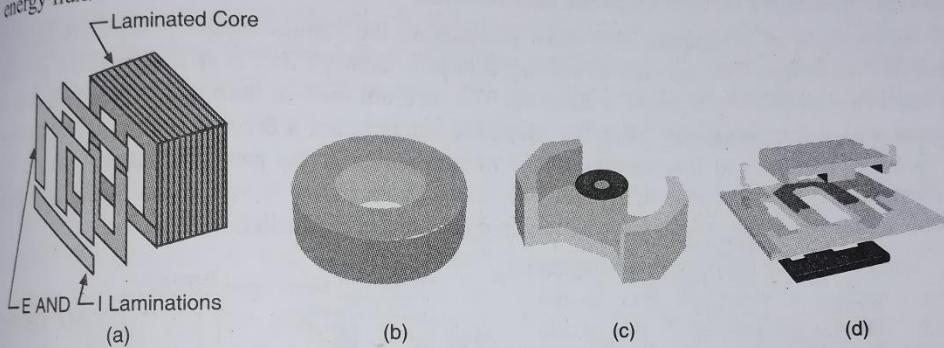


Fig. 41.24:

Different types of transformer cores- (a) Steel laminated core (b) toroidal core (c) Pot core (d) planar core

Solid Cores: Solid cores, particularly the powdered iron cores used in circuits, have high magnetic permeability as well as electrical resistance. When used in circuits, they tend to work best for transmission levels above main frequencies. For frequencies that tend to range even higher, such as those beyond the VHF (very high frequency) band, powdered iron is replaced by ferrites.

Toroidal Cores: A range of materials are available for use in toroidal cores, including steel, coiled permalloys, powdered iron, or ferrites. These cores can be circular in structure, with the rest of the transformer built around the core ring—the lack of an opening in the core ring means no air gaps—or they can be a long strip of material. The advantage of using a strip is reduced resistance as a result of properly aligned grain boundaries.

Toroidal cores are more efficient at handling the same kind of energy load than steel laminated E shape cores, and can be made smaller, lighter, and with a lower magnetic field. However, windings tend to be more expensive for toroidal cores.

Pot core: The shape of a pot core is round with an internal hollow that almost completely encloses the coil. Usually a pot core is made in two halves which fit together around a coil former. This design of core has a shielding effect which reduces electromagnetic interference.

Planar core: A planar core consists of two flat pieces of magnetic material, one above and one below the coil. It is typically used with a flat coil that is part of a printed circuit board. This design is excellent for **mass production** and allows a high **power**, small **volume** **transformer** to be constructed for low cost. It is not as ideal as either a pot core or toroidal core but costs less to produce.

(ii) Magnetic Storage: Data storage devices are the essential requirements of entertainment electronics and computer systems. There are two types of storage devices available, namely semiconductor memories in which flip-flops are the storage elements and magnetic memories in which the magnetic domains are the storage elements. The semiconductor memories are *volatile* whereas the magnetic memories are permanent and *non-volatile*.

The most common form of storage technology is magnetic storage. The data and programs required for computer operations are stored on magnetic bulk storage devices like tapes and disks. Magnetic storage and magnetic recording means storage of information on a magnetized medium. Magnetic storage was first suggested by Oberlin Smith in 1888. The first working magnetic recorder was invented by Valdemar Poulsen in 1898 and in 1928; Fritz Pfeumer developed the first magnetic tape recorder.

In the field of computing and video production, the storage media is typically called a **disk** or a **cartridge**. The process of storing data in a memory unit is writing and the process of retrieving data from memory is **reading**. The medium used in magnetic-storage devices is coated with a **ferromagnetic** material. Magnetic storage uses a drive, which is a mechanical device that connects to the computer. The media, which is the part that actually stores the information, is inserted into the drive. The drive uses a motor to rotate the media at a high speed, and it reads the stored information using small devices called **heads**.

Each head has a tiny electromagnet which applies a **magnetic flux** to the oxide on the media, and the oxide permanently “remembers” the flux. In writing, the data signal is sent through the coil of wire to create a magnetic field in the core (Fig. 41.25). At the gap, the magnetic flux forms a fringe pattern and the flux magnetizes the oxide on the media. When the data is read by the drive, the **read head** pulls a varying magnetic field across the gap, creating a varying magnetic field in the core and therefore a signal in the coil. This signal is then sent to the computer as binary data.

(a) Hard disks: Magnetic disk memories provide large storage capabilities with moderate operating speed. A magnetic disk is a flat, circular plate called **platter** which has a surface that is coated with magnetic iron oxide particles. It also has a read-write head that hovers over the surface to read data.

A *hard disk* is one or more platters and their associated read-write heads. The platters rotate at very high speed of the order of 3600 rpm. The information is stored on their surface by magnetic heads mounted on access arms. Information is recorded in the form of bands.

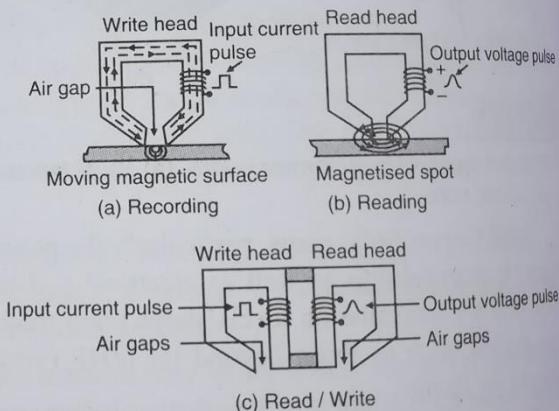


Fig. 41.25:

Magnetic recording and reading

Each band of information on a particular disk is called a **track**. The tracks are divided into **sectors** (see Fig. 41.26). Tracks and sectors are created when the hard disc is first **formatted** and this must take place before the disc can be used. The tracks are arranged in **concentric rings** so the software can jump from "file 1" to "file 19" without having to fast forward through files 2 through 18. There will be several thousand data tracks on one side of a disk in which the bits are recorded in a track at a density of the order of 20,000 to 1,00,000 bits/inch.

A typical outer track contains more bits than the inner tracks since the circumference of an outer track is greater. The disk or cartridge spins like a record and the heads move to the correct track, providing what is known as **direct-access storage**.

The total time taken by the head to begin reading or to begin writing on a selected track is called **access time**. The time taken to position a head on the selected track is called **seek time** which is of the order of milliseconds. The time required for the desired data to reach the magnetic head after the positioning of the head is called **rotational delay**.

The time requirement will be of the order of milliseconds. The total access time for a disk is the sum of the seek time and rotational delay. The number of bits transferred per second once reading or writing begins is called transfer rate of disk. A schematic diagram of a flying head is shown in Fig. 41.27.

When the magnetic disk rotates, a thin but resilient layer of air rotates along with the disk. The shape of the head is designed in such a way that it rides on this layer of air causing the disk to maintain separation from the head. It floats on a cushion of air a fraction of a millimetre above the surface of the disc. The drive is inside a sealed unit because even a speck of dust could cause the heads to crash.

The storage capacity in the modern disk memories is increased by mounting several disks on a common drive unit known as disk pack as shown in Fig. 41.28. During the operation of the memory, the disks are rotated at a uniform speed by a disk drive unit. Each recording surface consists of one read-write head. Using the movable arm connected with the disks, a particular set of track for reading/

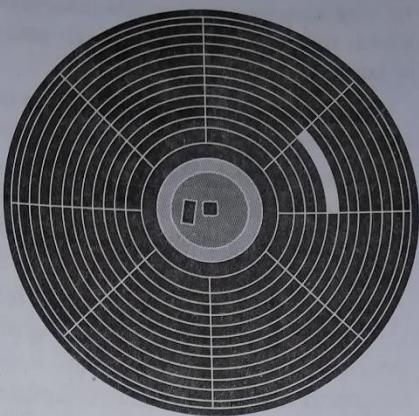


Fig. 41.26:

Tracks and sectors on a hard disk

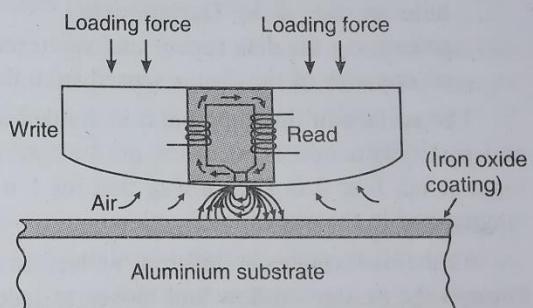


Fig. 41.27:

Schematic diagram of a flying head

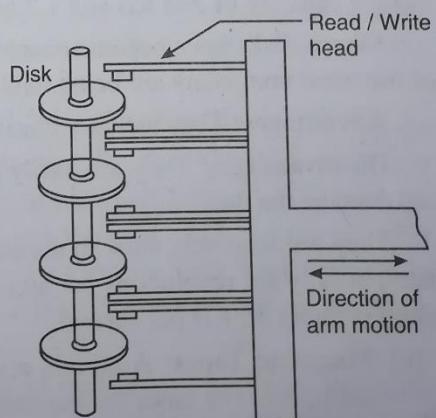


Fig. 41.28:

Disk pack

writing can be selected. The magnetic disk memories are relatively inexpensive, have low access time and high disk transfer rate. Hard disks of size 80 to 250 GB have become common in latest personal computers.

Advantages: Very fast access to data. Data can be read directly from any part of the hard disc (**random access**). The access speed is about **1000 KB per second**.

(b) **Floppy disks:** The floppy disk is a small flexible direct access magnetic storage device. It is made of very thin and flexible Mylar (plastic) material. The surface of the disk is coated with a thin magnetic film. It is permanently housed in a square jacket for protective purpose as illustrated in Fig. 41.29. The index hole establishes a reference point for all the tracks on the disc. The outer circle shows a hole in the jacket while the inner circle shows the index hole in the disk. During data processing the disk rotates and when the two holes are aligned a beam of light shining on one side of the disc is sensed from the other side and is used for timing functions.

The surface of the floppy disc is divided into a number of concentric circles called tracks and the information is recorded on the tracks. Tiny magnetic spots are used to record the logic states 1 or 0 in such a way that for 1 it is magnetized in one direction and for 0, it is magnetized in the opposite direction.

As the disk rotates at 360 rpm within the fixed jacket, the read/write head makes contact through the access window and moves to specified position along the length of the slot. The write protect notch is used to protect the stored information. A typical $5\frac{1}{4}$ inch floppy disk is organized into 77 tracks and is divided into 26 sectors. Thus, each track is divided into 26 equal-sized sectors. The $5\frac{1}{4}$ inch disk is available with double density and high density with storage capacity of 360 KB and 1.2 MB.

Floppy disks have become obsolete because of their low capacity range and so now most of the latest computers are being made without a floppy disk drive.

Advantages: They are very cheap to buy and floppy disc drives are very common.

Disadvantages: They are easily physically damaged if unprotected and magnetic fields can damage the data.

They are relatively slow to access because floppy discs rotate far more slowly than hard discs, at only six revolutions per second, and only start spinning when requested. The access speed is about 36 KB per second.

(c) **Magnetic Tapes:** A tape is a type of backup storage device used to copy data on a hard disk. The tapes are generally thin flexible plastic tapes with a thin coating of hard magnetic material on one side. The magnetic material must have high remanent magnetization and least sensitivity for self-demagnetization. As such materials with rectangular

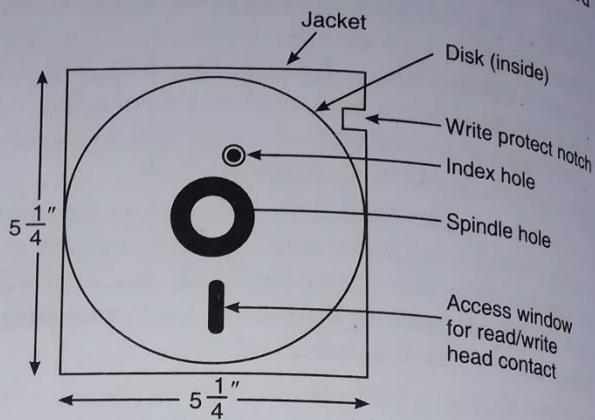


Fig. 41.29:

Illustration of floppy disk

hysteresis loop are used in making the coating. Just like the tape in a tape-recorder, the data is written to or read from the tape as it passes the magnetic heads.

Data on a tape is arranged as a long sequence, beginning at one end of the tape and stretching to the other end. Therefore a tape is a sequential storage device whereas hard disks and floppies are random access storage devices. Access time on a tape is measured in seconds, unlike hard disk drives which are measured in milliseconds. Tape drives have good storage capacity, being able to hold as much information as a hard disk. Most tape drives can back up 1GB of data in 15-20 minutes. Tape storage is not suitable for daily tasks because it is too slow to be the computers main storage device.

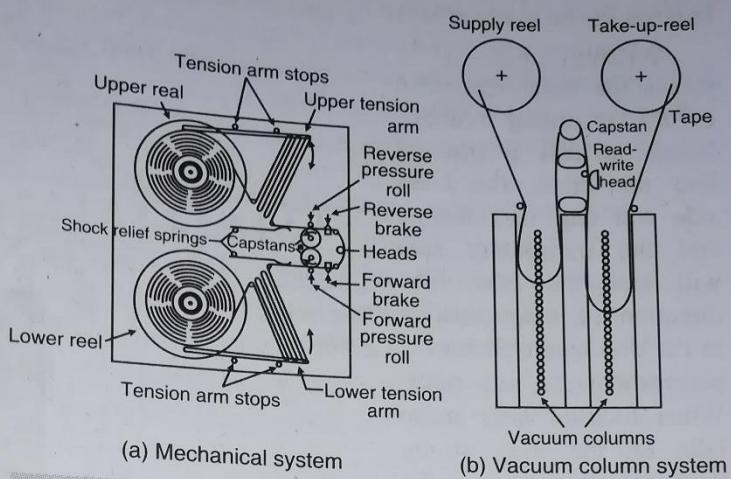


Fig. 41.30:

Illustration of tape mechanism

Fig. 41.30 shows a high speed start-stop tape mechanism which uses a set of tension arms around which the tape is laced. The tension arms are movable and when the tape is suddenly driven past the heads by the capstan, the mechanism provides a buffering supply of tape. A servo mechanism is used to drive the upper and lower reels to maintain sufficient tape between capstan and tape reels.

Output signals from read heads are generally in the range of 0.1 to 0.5 V. the recording density varies from few hundred bits/inch to several thousand bits/inch. Data are recorded on magnetic tape by using some coding system. Usually one character is stored per row along the tape.

Advantages: Magnetic tape is relatively cheap and tape cassettes can store very large quantities of data (*typically 26 GB*).

Disadvantages: Accessing data is very slow and we cannot go directly to an item of data on the tape as we can with a disc. It is necessary to start at the beginning of the tape and search for the data as the tape goes past the heads (serial access).

(iii) Magneto-optical Recording: Compact discs are classified based on the storage techniques and capabilities as CD-ROM (Read only Memory), CD-WORM (Write Once Read Many), CD-R/W (Read/Write) etc. They use different materials but write and read the data using a laser beam. In case of CD(R/W), we can write the data, read and rewrite after erasure. Erasability denotes that the recording media can undergo a very large number of write/erase operations without any loss. Magneto-optical (MO) systems write magnetically and read optically.

Principle: A laser beam is used for writing, reading and erasing of data on a magneto-optical medium. A weak laser also generates high local temperatures when focused at a small spot on the medium. Generally the Curie temperature is of the order of 200°C for magnetic materials. As the coercivity of material drops at higher temperatures, the magnetization can

be changed by applying a weak magnetic field at higher temperatures. When the material is cooled to room temperature, its coercivity rises back to such a high level that the magnetic data cannot be easily affected by the regular magnetic fields.

Writing: Fig. 41.31 shows the basic schematic of the recording process. When the disk is inserted into the drive, the label side will face the magnet, and the transparent side will face the laser. The direction of magnetization in the thin magnetic film is perpendicular to the surface. When focused laser pulse falls on the film, strong localized heating occurs. At the high temperature, domain reversal takes place due to the action of the downward magnetic field and the upward atomic magnets turn downward.

Reading: Magneto-optic systems use polarized light to read the data from the disk. The changes in light polarization occur due to the presence of a magnetic field on the surface of the disk. If a beam of polarized light is reflected from a magnetized surface, the polarization of the reflected beam will change a little. If the magnetization is reversed, the change in polarization is also reversed. The change in direction of magnetization could be associated with numbers 0 or 1, making this technique useful for binary data storage.

Magneto-optic Erasing: To erase the data, magnetic field is applied in the upward direction. The focused laser pulse causes local heating which assists the atomic magnets to turn in the upward direction. Thus, data is written, read, erased and rewritten on the MO disc.

Design of MO disk: A thin film of amorphous Terbium iron cobalt (TbFeCo) magnetic film is coated on a substrate. It is the active medium. The active magneto-optical layer is in fact enclosed between thin dielectric layers. The layers act as 'anti-reflection layers' and

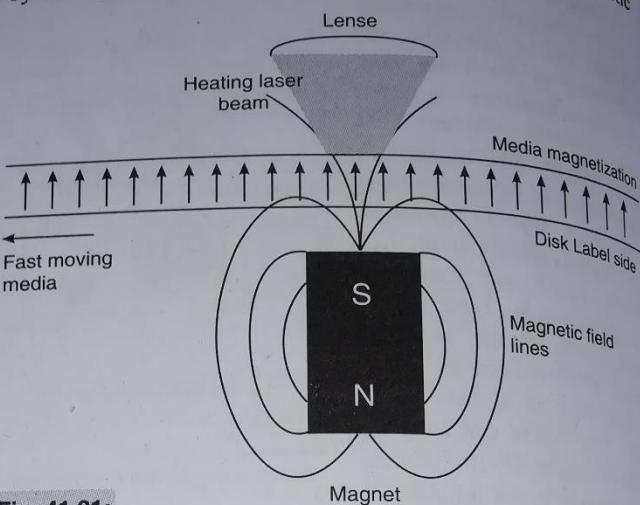


Fig. 41.31:

Schematic of the magneto-optic recording process

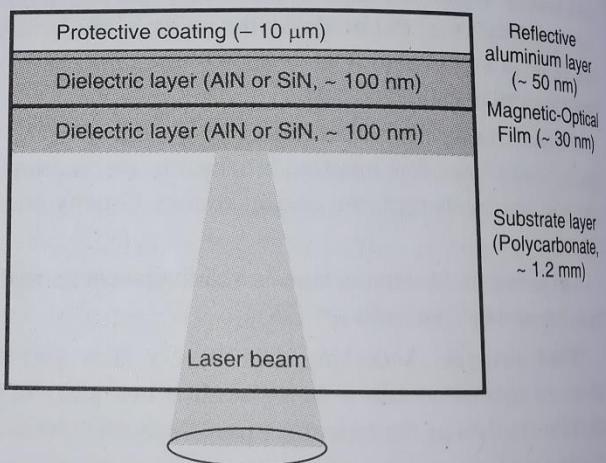


Fig. 41.32:

Design of a quadrilayer magneto-optical disk

increase light absorption by the active layer. On top of these layers, a thin aluminium layer is coated. The aluminium layer acts as a light reflector and a heat sink to minimize lateral heating of the active layer.