11. MAGNETIC PROPERTIES

Introduction : The basic aim in the study of the subject of magnetic materials is to understand the effect of an external magnetic field on a bulk material ,and also to account for its specific behavior. A dipole is an object that a magnetic pole is on one end and a equal and opposite second magnetic dipole is on the other end.

A bar magnet can be considered as a dipole with a north pole at one end and South Pole at the other. If a magnet is cut into two, two magnets or dipoles are created out of one. This sectioning and creation of dipoles can continue to the atomic level. Therefore, the source of magnetism lies in the basic building block of all the matter i.e. the atom.

Consider electric current flowing through a conductor. When the electrons are flowing through the conductor, a magnetic field is forms around the conductor. A magnetic field is produced whenever an electric charge is in motion. The strength of the field is called the **magnetic moment.**

Magnetic materials are those which can be easily magnetized as they have permanent magnetic moment in the presence of applied magnetic field. Magnetism arises from the magnetic dipole moments. It is responsible for producing magnetic influence of attraction or repulsion.

Magnetic dipole : it is a system consisting of two equal and opposite magnetic poles separated by a small distance of '2l'metre.

Magnetic Moment (μ_m) :It is defined as the product of the pole strength (m) and the distance between the two poles (2l) of the magnet.

$$i.e.. \quad \mu_m = (2l)\, m$$

Units: Ampere – metre^2

Magnetic Flux Density or Magnetic Induction (B): It is defined as the number of magnetic lines of force passing perpendicularly through unit area.

$$i.e.. \quad \mathbf{B} = \text{magnetic flux / area} = \Phi / A$$

Units: Weber / metre^2 or Tesla.

Permeability:

Magnetic Field Intensity (H): The magnetic field intensity at any point in the magnetic field is the force experienced by a unit north pole placed at that point.

Units: Ampere / meter

The magnetic induction B due to magnetic field intensity H applied in vacuum is related by

$\mathbf{B} = \mu_0 \mathbf{H}$ where μ_0 is permeability of free space = $4 \Pi \times 10^{-7}$ H / m

If the field is applied in a medium, the magnetic induction in the solid is given by

$\mathbf{B} = \mu \mathbf{H}$ where μ is permeability of the material in the medium

$\mu = B / H$

Hence magnetic Permeability μ of any material is the ratio of the magnetic induction to the applied magnetic field intensity. The ratio of μ / μ_0 is called the relative permeability (μ_r).

$\mu_r = \mu / \mu_0$

Therefore $\mathbf{B} = \mu_0 \mu_r \mathbf{H}$

Magnetization: It is the process of converting a non – magnetic material into a magnetic material. The intensity of magnetization (M) of a material is the magnetic moment per unit volume. The intensity of magnetization is directly related to the applied field H through the susceptibility of the medium (χ) by

$\chi = M / H$ ----------(1)

The magnetic susceptibility of a material is the ratio of the intensity of magnetization produced to the magnetic field intensity which produces the magnetization. It has no units.

We know

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

$= \mu_0 \mu_r \mathbf{H}$

i.e $\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mu_0 \mathbf{H} - \mu_0 \mathbf{H}$

$= \mu_0 \mathbf{H} + \mu_0 \mathbf{H} (\mu_r - 1)$

$= \mu_0 \mathbf{H} + \mu_0 \mathbf{M}$ where M is magnetization = $\mathbf{H} (\mu_r - 1)$

i.e $\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$ ----------(2)

The first term on the right side of eqn (2) is due to external field. The second term is due to the magnetization.

Hence $\mu_0 = \mathbf{B / H + M}$

Relative Permeability ,

$\mu_r = \mu / \mu_0 = (\mathbf{B / H}) / (\mathbf{B / H + M}) = \mathbf{H + M / H} = 1 + M / H$

$\mu_r = 1 + \chi$ **---------(3)**

The magnetic properties of all substances are associated with the orbital and spin motions of the electrons in their atoms. Due to this motion, the electrons become elementary magnets of the substance. In few materials these elementary magnets are able to strengthen the applied magnetic field , while in few others , they orient themselves such that the applied magnetic field is weakened.

Origin of Magnetic Moment : In atoms , the permanent magnetic moments can arise due to the following :

1. the orbital magnetic moment of the electrons
2. the spin magnetic moment of the electrons
3. the spin magnetic moment of the nucleus.

Orbital magnetic moment of the electrons: In an atom, electrons revolve round the nucleus in different circular orbits.

Let m be the mass of the electron and r be the radius of the orbit in which it moves with angular velocity ω.

The electric current due to the moving electron I = - (number of electrons flowing per second x charge of an electron)

Therefore $I = - e \omega / 2 \Pi$ ----------(1)

The current flowing through a circular coil produces a magnetic field in a direction perpendicular to the area of coil and it is identical to the magnetic dipole. the magnitude of the magnetic moment produced by such a dipole is

$$\mu_m = I . A$$

$$= (- e \omega / 2 \Pi) (\Pi r^2)$$

$$= - e \omega r^2 / 2 = (- e / 2 m) (m \omega r^2) = - (e / 2 m) L \text{ ----------(2)}$$

where $L = m \omega r^2$ is the orbital angular momentum of electron. The minus sign indicates that the magnetic moment is anti – parallel to the angular momentum L. A substance therefore possesses permanent magnetic dipoles if the electrons of its constituent atom have a net non-vanishing angular momentum. The ratio of the magnetic dipole moment of the electron due to its orbital motion and the angular momentum of the orbital motion is called orbital gyro magnetic ratio , represented by γ.

Therefore γ = magnetic moment / angular momentum = e / 2m

The angular momentum of an electron is determined by the orbital quantum number ‘l’ given by l = 0 , 1 , 2 , ……(n – 1) where n is principal quantum number n = 1 , 2 , 3 , 4 , …… ……corresponding to K , L , M , N……shells .
The angular momentum of the electrons associated with a particular value of l is given by $l(h / 2 \Pi)$

The strength of the permanent magnetic dipole is given by

$$\mu_{el} = - (e / 2 m) (l h / 2 \Pi)$$

i.e $\mu_{el} = -(e h l / 4 \Pi m) = -\mu_B l$ ----------(3)

The quantity $\mu_B = e h / 4 \Pi m$ is an atomic unit called Bohr Magneton and has a value 9.27 x 10^{-24} ampere $metre^2$

In an atom having many electrons, the total orbital magnetic moment is determined by taking the algebraic sum of the magnetic moments of individual electrons. The moment of a completely filled shell is zero. An atom with partially filled shells will have non zero orbital magnetic moment.

Magnetic Moment Due to Electron Spin : The magnetic moment associated with spinning of the electron is called spin magnetic moment μ_{es} .Magnetic moment due to the rotation of the electronic charge about one of the diameters of the electron is similar to the earth's spinning motion around it's north – south axis.

An electronic charge being spread over a spherical volume ,the electron spin would cause different charge elements of this sphere to form closed currents, resulting in a net spin magnetic moment. This net magnetic moment would depend upon the structure of the electron and its charge distribution.

$\mu_{es} = \gamma (e / 2 m) S$ ----------(1)where $S = h / 4 \Pi$ is spin angular momentum

therefore $\mu_{es} \approx 9.4 \times 10^{-24}$ ampere $metre^2$

Thus, the magnetic moments due to the spin and the orbital motions of an electron are of the same order of magnitude. The spin and electron spin magnetic moment are intrinsic properties of an electron and exist even for a stationary electron. Since the magnitude of spin magnetic moment is always same, the external field can only influence its direction. If the electron spin moments are free to orient themselves in the direction of the applied field B. In a varying field ,it experiences a force in the direction of the increasing magnetic field due to spin magnetic moments of its various electrons.

Magnetic Moment due to Nuclear Spin : Another contribution may arise from the nuclear magnetic moment. By analogy with Bohr Magneton, the nuclear magneton arises due to spin of the nucleus. It is given by

$\mu_{ps} = e h / 4 \Pi M_p$

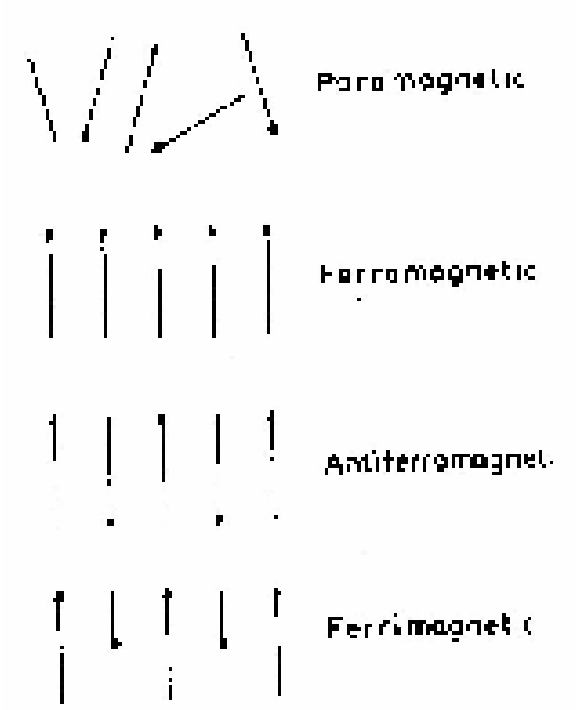
$\mu_{ps} = 5.05 \times 10^{-27}$ ampere $metre^2$ where M_p is mass of proton.

The nuclear magnetic moments are smaller than those associated with electrons.

Classification Of Magnetic Materials :All matter respond in one way or the other when subjected to the influence of a magnetic field. The response could be strong or weak, but there is none with zero response ie, there is no matter which is non magnetic in the absolute sense. Depending upon the magnitude and sign of response to the applied field , and also on the basis of effect of temperature on the magnetic properties, all materials are classified broadly under 3 categories.

1. Diamagnetic materials 2. Paramagnetic materials, 3. Ferromagnetic materials

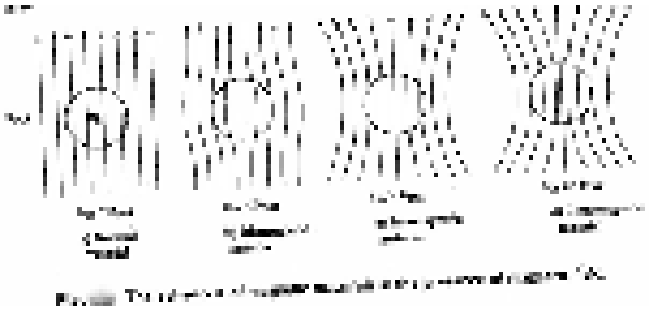
two more classes of materials have structure very close to ferromagnetic materials but possess quite different magnetic effects. They are i. Anti ferromagnetic materials and ii . Ferri magnetic materials



1. ***Diamagnetic materials: Diamagnetic*** materials are those which experience a repelling force when brought near the pole of a strong magnet. In a non uniform magnetic field they are repelled away from stronger parts of the field.

In the absence of an external magnetic field , the net magnetic dipole moment over each atom or molecule of a diamagnetic material is zero.

Ex: Cu, Bi , Pb .Zn and rare gases.



Paramagnetic materials: Paramagnetic materials are those which experience a feeble attractive force when brought near the pole of a magnet. They are attracted towards the stronger parts of magnetic field. Due to the spin and orbital motion of the electrons, the atoms of paramagnetic material posses a net intrinsic permanent moment.

Susceptibility χ is positive and small for these materials. The susceptibility is inversely proportional to the temperature T.

$\chi \alpha 1/T$

$\chi = C/T$ where C is Curie's temperature.

Below superconducting transition temperatures, these materials exhibit the Para magnetism.

Examples: Al, Mn, Pt, $CuCl_2$.

Ferromagnetic Materials: Ferromagnetic materials are those which experience a very strong attractive force when brought near the pole of a magnet. These materials, apart from getting magnetized parallel to the direction of the applied field, will continue to retain the magnetic property even after the magnetizing field removed. The atoms of ferromagnetic materials also have a net intrinsic magnetic dipole moment which is due to the spin of the electrons.

Susceptibility is always positive and large and it depends upon temperature.

$$\chi = C / (T- \theta)$$ (only in paramagnetic region i.e., $T > \theta$)

θ is Curie's temperature.

When the temperature of the material is greater than its Curie temperature then it converts into paramagnetic material.

Examples: Fe, Ni, Co, MnO.

Antiferromagnetic matériels : These are the ferromagnetic materials in which equal no of opposite spins with same magnitude such that the orientation of neighbouring spins is in antiparallel manner are present.
Susceptibility is small and positive and it is inversely proportional to the temperature.

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

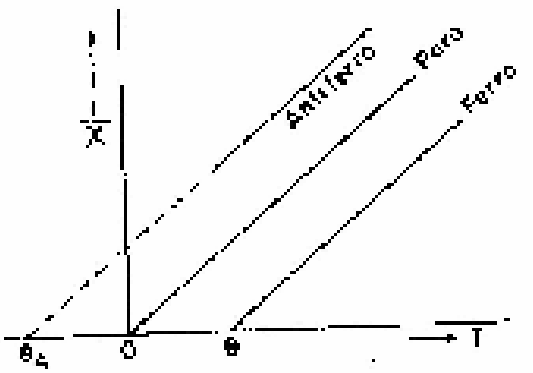
the temperature at which anti ferromagnetic material converts into paramagnetic material is known as Neel's temperature.

Examples: FeO, Cr_2O_3.

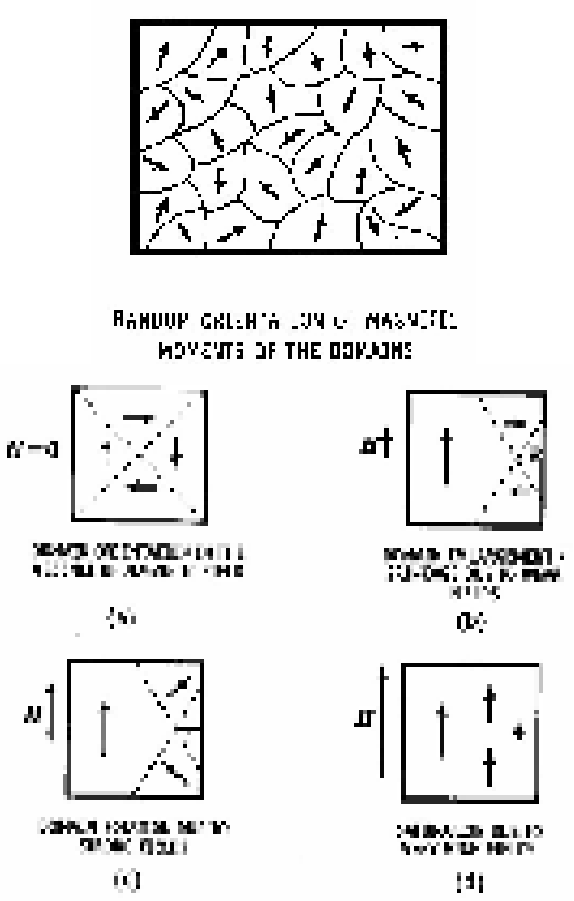
Ferrimagnetic materials: These are the ferromagnetic materials in which equal no of opposite spins with different magnitudes such that the orientation of neighbouring spins is in antiparallel manner are present.
Susceptibility positive and large, it is inversely proportional to temperature

$$\chi=C /(T \pm \theta) \qquad T> T_N$$ (Neel's temperature)

Examples : $ZnFe_2O_4$, $CuFe_2O_4$



Domain theory of ferromagnetism: According to Weiss, a virgin specimen of ferromagnetic material consists of a no of regions or domains (≈ 10-6 m or larger) which are spontaneously magnetized. In each domain spontaneous magnetization is due to parallel alignment of all magnetic dipoles. The direction of spontaneous magnetization varies from domain to domain. The resultant magnetization may hence be zero or nearly zero. When an external field is applied there are two possible ways of alignment fo a random domain.

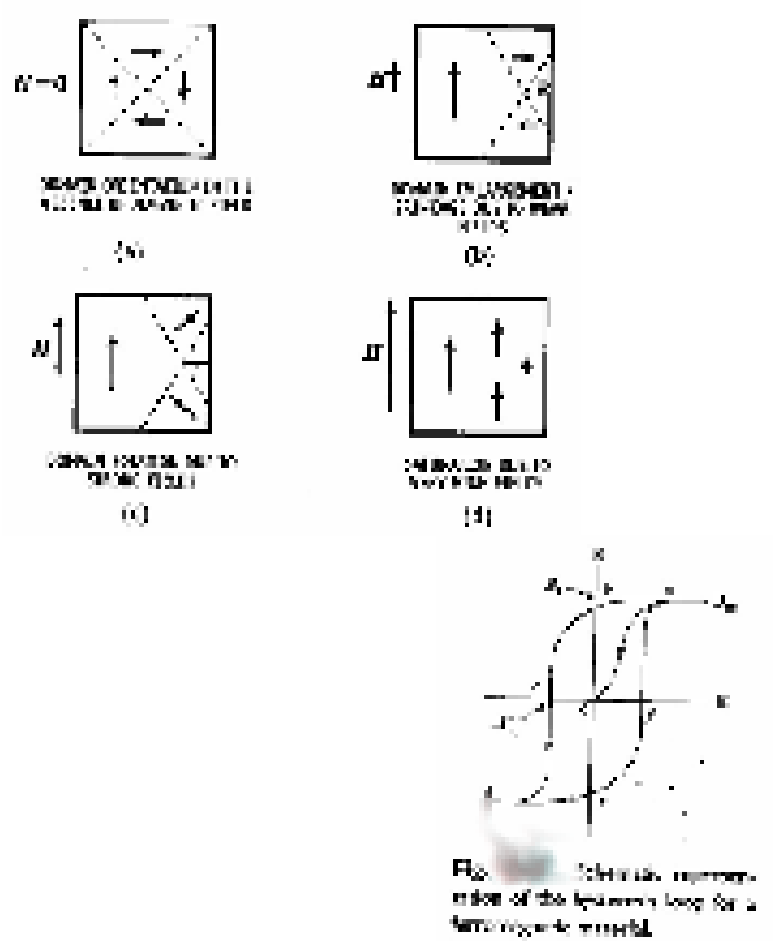


i). **By motion of domain walls:** The volume of the domains that are favourably oriented with respect to the magnetizing field increases at the cost of those that are unfavourably oriented

ii) **By rotation of domains**: When the applied magnetic field is strong, rotation of the direction of magnetization occurs in the direction of the field.

Hysteresis curve (study of B-H curve): The hysteresis of ferromagnetic materials refers to the lag of magnetization behind the magnetization field. when the temperature of the ferromagnetic substance is less than the ferromagnetic Curie temperature ,the substance exhibits hysteresis. The domain concept is well suited to explain the phenomenon of hysteresis. The increase in the value of the resultant magnetic moment of the specimen by the application of the applied field , it attributes to the 1. motion of the domain walls and 2. rotation of domains.

When a weak magnetic field is applied, the domains that are aligned parallel to the field and in the easy direction of magnetization , grow in size at the expense of less favorably oriented ones. This results in Bloch wall movement and when the weak field is removed, the domains reverse back to their original state. This reverse wall displacement is indicated by OA of the magnetization curve. When the field becomes stronger ,the Bloch wall movement continues and it is mostly irreversible movement. This is indicated by the path AB of the graph. The phenomenon of hysteresis is due to this irreversibility.



At the point B all domains have got magnetized along their easy directions. Application of still higher fields rotates the domains into the field direction which may be away from the easy direction. Once the domain rotation is complete the specimen is saturated denoted by C. on removal of the field the specimen tends to attain the original configuration by the movement of Bloch walls. But this movement is hampered by the impurities, lattice imperfections etc, and so more energy must be supplied to overcome the opposing forces. This means that a coercive field is required to reduce the magnetization of the specimen to zero. The amount of energy spent in this regard is a loss. Hysteresis loss is the loss of energy in taking a ferromagnetic body through a complete cycle of magnetization and this loss is represented by the area enclosed by the hysteresis loop.

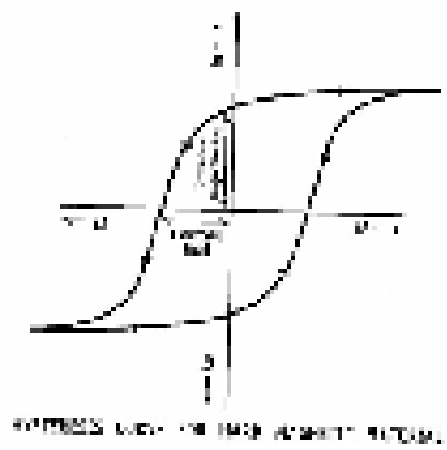
A hysteresis curve shows the relationship between the magnetic flux density B and applied magnetic field H. It is also referred to as the B-H curve(loop).

Hard and Soft Magnetic Materials:

Hysteresis loop of the ferromagnetic materials vary in size and shape. This variation in hysteresis loops leads to a broad classification of all the magnetic materials into hard type and soft type.

Hard Magnetic Materials:

Hard magnetic materials are those which are characterized by large hysteresis loop because of which they retain a considerable amount of their magnetic energy after the external magnetic field is switched off. These materials are subjected to a magnetic field of increasing intensity, the domain walls movements are impeded due to certain factors. The cause for such a nature is attributed to the presence of impurities or non-magnetic materials, or the lattice imperfections. Such defects attract the domain walls thereby reducing the wall energy. It results in a stable state for the domain walls and gives mechanical hardness to the material which increases the electrical resistivity. The increase in electrical resisitivity brings down the eddy current loss if used in a.c conditions. The hard magnetic materials can neither be easily magnetized nor easily demagnetized.



Properties:

1. High remanent magnetization
2. High coercivity
3. High saturation flux density
4. Low initial permeability
5. High hysteresis energy loss
6. High permeability
7. The eddy current loss is low for ceramic type and large for metallic type.

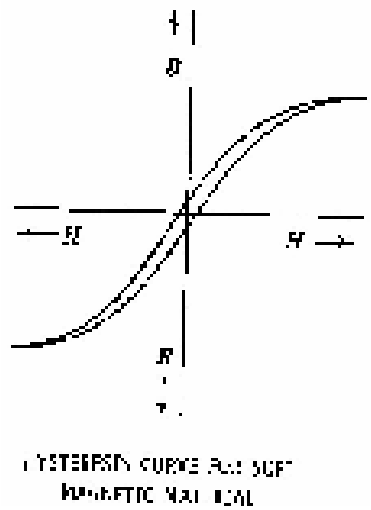
Examples of hard magnetic materials are, i) Iron- nickel- aluminum alloys with certain amount of cobalt called Alnico alloy. ii) Copper nickel iron alloys. iii) Platinum cobalt alloy.

Applications of hard magnetic materials: For production of permanent magnets, used in magnetic detectors, microphones, flux meters, voltage regulators, damping devices and magnetic separators.

Soft Magnetic Materials:

Soft magnetic materials are those for which the hysteresis loops enclose very small area. They are the magnetic materials which cannot be permanently magnetized. In these materials ,the domain walls motion occurs easily. Consequently, the coercive force assumes a small value and makes the hysteresis loop a narrow one because of which, the hysteresis loss

becomes very small. For the sane reasons, the materials can be easily magnetized and demagnetized.



Properties:

1. Low remanent magnetization
2. Low coercivity
3. Low hysteresis energy loss
4. Low eddy current loss
5. High permeability
6. High susceptibility

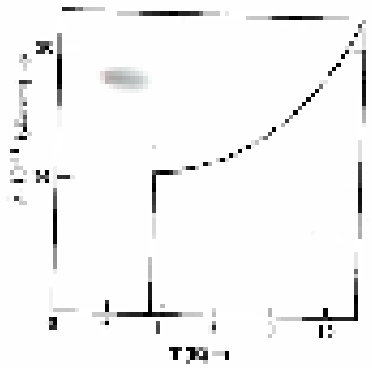
Examples of soft magnetic materials are

i) Permalloys (alloys of Fe and Ni)
ii) Si – Fe alloy
iii) Amorphous ferrous alloys (alloys of Fe, Si, and B)
iv) Pure Iron (BCC structure)

Applications of soft magnetic materials: Mainly used in electro- magnetic machinery and transformer cores. They are also used in switching circuits, microwave isolators and matrix storage of computers.

SUPERCONDUCTIVITY

Introduction : Certain metals and alloys exhibit almost zero resistivity(i.e. infinite conductivity) when they are cooled to sufficiently low temperatures. This phenomenon is called superconductivity. This phenomenon was first observed by H.K. Onnes in 1911. He found that when pure mercury was cooled down to below 4K, the resistivity suddenly dropped to zero. Since then hundreds of superconductors have been discovered and studied. Superconductivity is strictly a low temperature phenomenon. Few new oxides exhibited superconductivity just below 125K itself. This interesting phenomena has many important applications in many emerging fields.



General Properties: The temperature at which the transition from normal state to superconducting state takes place on cooling in the absence of magnetic field is called the critical temperature (Tc) or the transition temperature.

The following are the general properties of the superconductors:

1. The transition temperature is different to different substances.

2. For a chemically pure and structurally perfect specimen, the superconducting transition is very sharp.

3. Superconductivity is found to occur in metallic elements in which the number of valence electrons lies between 2 and 8.

4. Transition metals having odd number of valence electrons are favourable to exhibit superconductivity while metals having even number of valence electrons are unfavourable.

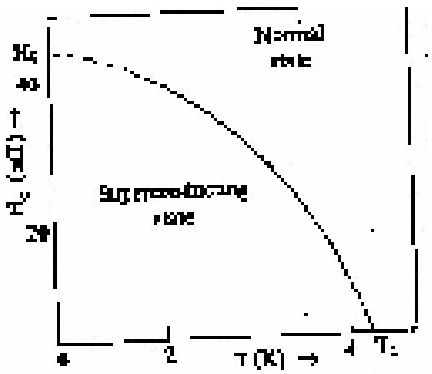
5. Materials having high normal resistivities exhibit superconductivity.

6. Materials for which $Z\rho > 106$ (where Z is the no. of valence electrons and ρ is the resistivity) show superconductivity.

7. Ferromagnetic and antiferromagnetic materials are not superconductors.

8. The current in a superconducting ring persists for a very long time .

Effect of Magnetic Field: Superconducting state of metal depends on temperature and strength of the magnetic field in which the metal is placed. Superconducting disappears if the temperature of the specimen is raised above Tc or a strong enough magnetic field applied. At temperatures below Tc, in the absence of any magnetic field, the material is in superconducting state. When the strength of the magnetic field applied reaches a critical value Hc the superconductivity disappears.



At T= Tc, Hc = 0. At temperatures below Tc, Hc increases. The dependence of the critical field upon the temperature is given by

$$H_C(T) = H_C(0)\,[1 - (T/Tc)^2]\text{----------(1)}$$

Where Hc(0) is the critical field at 0K. Hc(0) and Tc are constants of the characteristics of the material.

Meissner effect: When a weak magnetic field applied to super conducting specimen at a temperature below transition temperature Tc , the magnetic flux lines are expelled. This specimen acts as on ideal diamagnet. This effect is called meissner effect. This effect is reversible, i.e. when the temperature is raised from below Tc , at T = Tc the flux lines suddenly start penetrating and the specimen returns back to the normal state. Under this condition, the magnetic induction inside the specimen is given by

$$B = \mu_0(H + M) \quad \text{----------(2)}$$

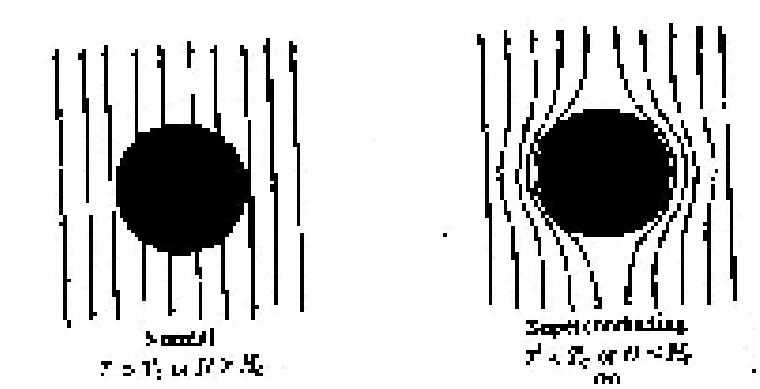
Where H is the external applied magnetic field and M is the magnetization produced inside the specimen.

When the specimen is super conducting, according to meissner effect inside the bulk semiconductor B= 0.

Hence $\mu_0(H + M) = 0$

Or $M = - H$ ----------(3)

Thus the material is perfectly diamagnetic.



Magnetic susceptibility can be expressed as

$\chi = M/H = -1$----------(4)

Consider a superconducting material under normal state. Let J be the current passing through the material of resistivity ρ. From ohm's law we know that the electric field

$$E = J\rho$$

On cooling the material to its transition temperature, ρ tends to zero. If J is held finite.

E must be zero. Form Maxwell's eqn, we know

$\nabla \times E = -dB/dt$ ----------(5)

Under superconducting condition since E = 0, dB/dt = 0, or B= constant.

This means that the magnetic flux passing through the specimen should not change on cooling to the transition temperature. The Meissner effect contradicts this result.

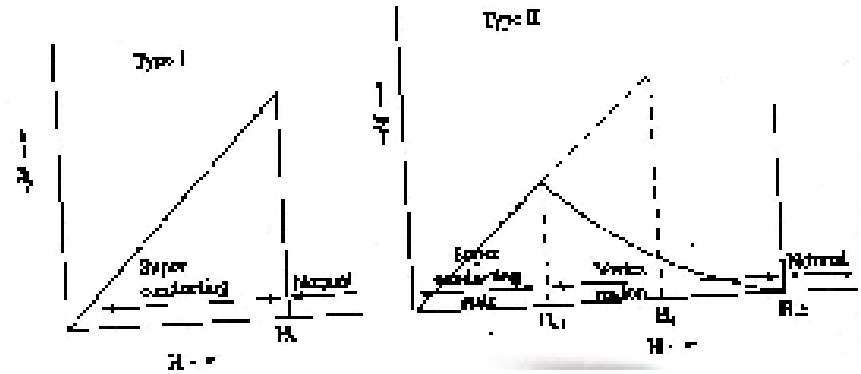
According to Meissner effect perfect diamagnetism is an essential property of defining the superconducting state. Thus

From zero resistivity E = 0,

From Meissner effect B= 0.

***Type- I , Type- II superconductors*:** Based on diamagnetic response Superconductors are divided into two types, i.e type-I and type-II.

Superconductors exhibiting a complete Meissner effect are called type-1, also called Soft Superconductors. When the magnetic field strength is gradually increased from its initial value H< HC, at HC the diamagnetism abruptly disappear and the transition from superconducting state to normal state is sharp. Example Zn, Hg, pure specimens of Al and Sn.



In type-2 Superconductors, transition to the normal state takes place gradually. For fields below H_{C1}, the material is diamagnetic i.e., the field is completely excluded H_{C1} is called the lower critical field. At H_{C1} the field begins to penetrate the specimen. Penetration increases until H_{C2} is reached. At H_{C2}, the magnetizations vanishes i.e., the material becomes normal state. H_{C2} is the upper critical field. Between H_{C1} and H_{C2} the state of the material is called the mixed or vortex state. They are also known as hard superconductors. They have high current densities. Example Zr , Nb etc.

Penetration Depth : The penetration depth λ can be defined as the depth from the surface at which the magnetic flux density falls to 1/e of its initial value at the surface. Since it decreases exponentially the flux inside the bulk of superconductor is zero and hence is in agreement with the Meissner effect. The penetration depth is found to depend on temperature. its dependence is given by the relation

$$\lambda (T) = \lambda (0) (1 - T^4 / T_c^4)^{-1/2} \quad \text{----------(1)}$$

where $\lambda (0)$ is the penetration depth at T = 0K.

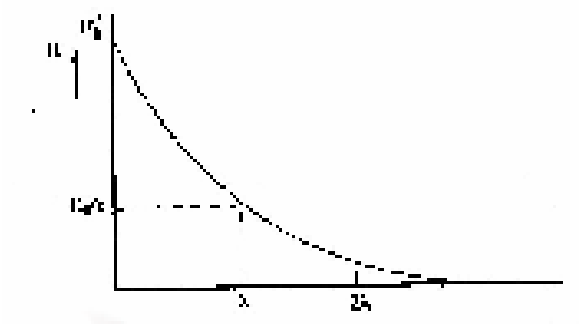


Fig. Exponential decrease of the magnetic Field inside a superconductor.

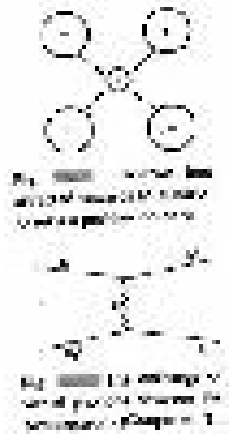
According to eqn.(1) , λ increases with the increase of T and at T= T_c , it becomes infinite . At T= T_c , the substance changes from super conducting state to normal state and hence the field can penetrate to the whole specimen , ie , the specimen has an infinite depth of penetration.

BCS Theory : BCS theory of superconductivity was put forward by Bardeen, Cooper and Schrieffer in 1957. This theory could explain many observed effects such as zero resistivity , Meissner effect, isotope effect etc. The BCS theory is based on advanced quantum concept.

1. *Electron – electron interaction via lattice deformation:* Consider an electron is passing through the lattice of positive ions. The electron is attracted by the neighbouring positive ion, forming a positive ion core and gets screened by them. The screening greatly reduces the effective charge of this electron. Due to the attraction between the electron and the positive ion core, the lattice gets deformed on local scale. Now if another electron passes by its side of the assembly of the electron and the ion core, it gets attracted towards it. The second electron interacts with the first electron via lattice deformation. The interaction is said to be due to the exchange of a virtual phonon ,q, between the two electrons. The interaction process can be written in terms of wave vector k ,as

$$K_1 - q = K_1^1 \quad \text{and} \quad K_2 + q = K_2^1 \quad \text{----------(1)}$$

This gives $K_1 - K_2 = K_1^1 + K_2^1$, ie , the net wave vector of the pair is conserved. The momentum is transferred between the electrons. These two electrons together form a cooper pair and is known as cooper electron.



2. *Cooper Pair:* To understand the mechanism of cooper pair formation , consider the distribution of electrons in metals as given by Fermi – Dirac distribution function .

$$F(E) = 1 / [\exp(E - E_F / KT) + 1]$$

At T = 0K, all the energy states below Fermi level E_F are completely filled and all the states above are completely empty.

Let us see what happens when two electrons are added to a metal at absolute zero. Since all the quantum states with energies $E \leq E_F$ are filled , they are forced to occupy states having energies $E > E_F$. Cooper showed that if there is an attraction between the two electrons ,they are able to form a bound state so that their total energy is less than 2 E_F .

These electrons are paired to form a single system. These two electrons together form a cooper pair and is known as cooper electron. cooper pair and is known as cooper electron. Their motions are correlated. The binding is strongest when the electrons forming the pair have opposite momenta and opposite spins. All electron pairs with attraction among them and lying in the neighbourhood of the Fermi surface form cooper pairs. These are super electrons responsible for the superconductivity.

In normal metals, the excited states lie just above the Fermi surface. To excite an electron from the Fermi surface even an arbitrarily small excitation energy is sufficient. In super conducting material , when a pair of electrons lying just below the Fermi surface is taken just above it ,they form a cooper pair and their total energy is reduced. This continues until the system can gain no additional energy by pair formation. Thus the total energy of the system is further reduced.

At absolute zero in normal metals there is an abrupt discontinuity in the distribution of electrons across the Fermi surface whereas such discontinuity is not observed in superconductors. As super electrons are always occupied in pairs and their spins are always in opposite directions.

Isotope Effect : in super conducting materials, the transition temperature varies with the average isotopic mass , M , of their constituents. The variation is found to follow the general form

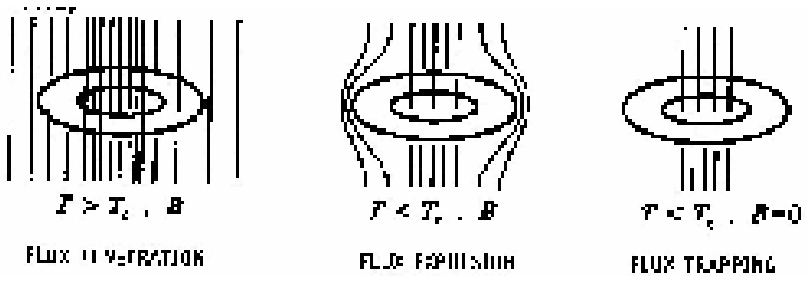
$$T_c \ \alpha \ M^{-\alpha} \quad \text{----------(1)}$$

Or $M^{\alpha} \ T_c = \text{constant}$

Where α is called the isotope effect coefficient .

Flux Quantization:

Consider a superconductor in the form of a ring. Let it be at temperature above its T_C because of which it will be in the normal state. When it is subjected to the influence of a magnetic field, the flux lines pass through the body and also exist out side and inside ring also.



If the body is cooled to a temperature below its T_C, then as per Meissner effect, the flux lines are expelled from the body i.e. the flux exists both outside the ring and in the hole region but not in the body of the ring. But when the external field is switched off, the magnetic flux lines continue to exist within the hole region, through the rest that surrounded the ring from the exterior would vanish. This is known as flux trapping. It is due to the large currents that are induced as per Faraday's law during the flux decay when the field switched off. Because of the zero resistance property that the superconductor enjoys, these induced currents continue to circulate in the ring practically externally. Thus the flux stand trapped in the loop forever.

It was F.London who gave the idea that the trapped magnetic flux is quantized, as super conductivity is governed by the quantum phenomenon. At first he suggested the quantization of Φ as

$$\Phi = nh / e \qquad n = 1,2,3,\ldots\ldots\ldots$$

But experiments carried out carefully on very small superconducting hollow cylinders by Deaver and Fairbank , that gave half the values of flux quanta given by London. Thus the governing equation for flux quantization was changed to,

$$\mathbf{\Phi = nh / 2e}$$

It happened so because, London's theory was based on supercurrents constituted by electrons as individual entities. This demonstrates conclusively that superconducting current carriers are pairs of electrons and not single ones.

Then the above equation is written as

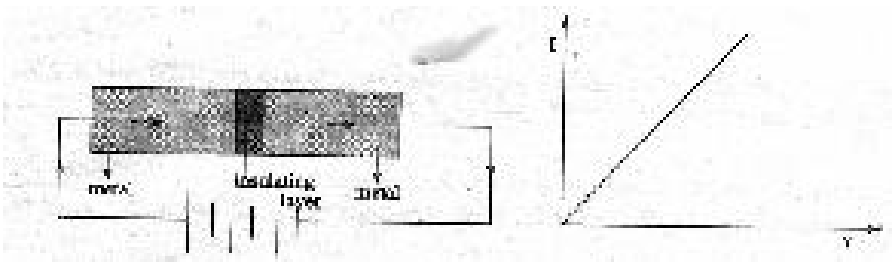
$$\mathbf{\Phi = n \Phi_0}$$

Where $\mathbf{\Phi_0 = (h/2e)}$ is the quantum of flux and is called fluxoid.

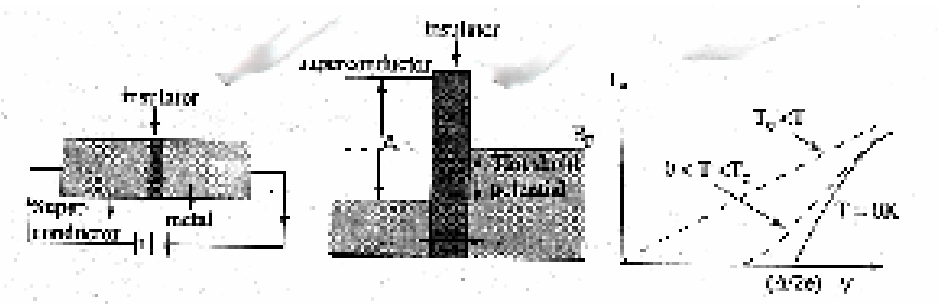
Josephson Effect : Consider a thin insulating layer sandwiched between two metals. This insulating layer acts as a potential barrier for flow of electrons from one metal to another. Since the barrier is so thin , mechanically electrons can tunnel through from a metal of higher chemical potential to the other having a lower chemical potential. This continues until the chemical potential of electrons in both the metals become equal.

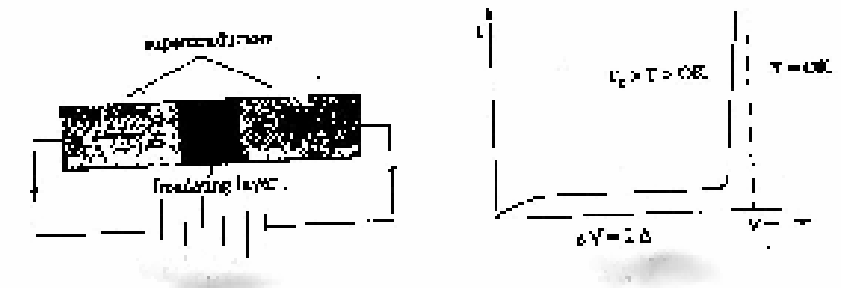
Consider application of a potential difference across the potential barrier. Now more electrons tunnel through the insulating layer from higher potential side to lower potential side. The current – voltage relation across the tunneling junction obeys the ohm's law at low voltages.

Now consider another case that one of the metals is a superconductor. On applying the potential, it can be observed that no current flows across the junction until the potential reaches a threshold value. It has been found that the threshold potential is nothing but half the energy gap in the superconducting state. Hence the measurement of threshold potential under this condition helps one to calculate the energy gap of superconductor. As the temperature is increased towards T_c ,more thermally excited electrons are generated. Since they require less energy to tunnel , the threshold voltage decreases. This results in decrease of energy gap itself.



Consider a thin insulating layer sandwiched between two superconductors. In addition to normal tunneling of single electrons, the super electrons also tunnel through the insulating layer from one superconductor to another without dissociation, even at zero potential difference across the junction. Their wave functions on both sides are highly correlated. This is known as Josephson effect.





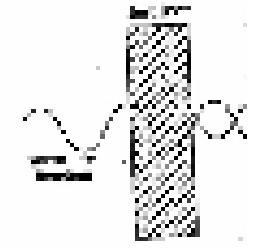
The tunneling current across the junction is very less since the two superconductors are only weakly coupled because of the presence of a thin insulating layer in between.

D.C. Josephson Effect : According to Josephson, when tunneling occurs through the insulator it introduces a phase difference $\Delta\Phi$ between the two parts of the wave function on the opposite sides of the junction.

The tunneling current is given by

$$I = I_0 \sin (\Phi_0) \text{ ----------(1)}$$

Where I_0 is the maximum current that flows through the junction without any potential difference across the junction. I_0 depends on the thickness of the junction and the temperature.



When there is no applied voltage, a d.c. current flows across the junction. The magnitude of the current varies between I_0 and $-I_0$ according to the value of phase difference $\Phi_0 = (\Phi_2 - \Phi_1)$. This is called d.c Josephson effect.

A.C. Josephson Effect : let a static potential V_0 is applied across the junction. This results in additional phase difference introduced by cooper pair during tunneling across the junction. This additional phase difference $\Delta\Phi$ at any time t can be calculated using quantum mechanics

$$\Delta\Phi = E\,t / \hbar \text{ ----------(1)}$$

Where E is the total energy of the system.

In the present case $E = (2\,e)\,V_0$. since a cooper pair contains 2 electrons , the factor 2 appears in the above eqn.

Hence $\Delta\Phi = 2\,e\,V_0\,t / \hbar$.

The tunneling current can be written as

$$I = I_0 \sin(\Phi_0 + \Delta\Phi) = I_0 \sin(\Phi_0 + 2\,e\,V_0\,t / \hbar) \text{ ----------(1)}$$

This is of the form

$$I = I_0 \sin(\Phi_0 + \omega\,t) \text{ ----------(2)}$$

Where $\omega = 2\,e\,V_0 / \hbar$.

This represents an alternating current with angular frequency ω. This is the a.c. Josephson effect. when an electron pair crosses the junction a photon of energy $\hbar\omega = 2eV_0$ is emitted or absorbed.



Current – voltage characteristics of a Josephson junction are :

1. When $V_0 = 0$, there is a constant flow of d.c current i_c through the junction. This current is called superconducting current and the effect is the d.c. Josephson effect.

2. So long $V_0 < V_c$, a constant d.c.current i_c flows.

3. When $V_0 > V_c$, the junction has a finite resistance and the current oscillates with a frequency $\omega = 2\,e\,V_0 / \hbar$. This effect is the a.c Josephson effect.

Applications Of Josephson Effect:

1. It is used to generate microwaves with frequency $\omega = 2\,e\,V_0 / \hbar$.

2. A.C Josephson effect is used to define standard volt.

3. A.C Josephson effect is also used to measure very low temperatures based on the variation of frequency of emitted radiation with temperature.

4. A Josephson junction is used for switching of signals from one circuit to another. The switching time is of the order of 1ps and hence very useful in high speed computers.

Applications Of Superconductors :

1. Electric generators : superconducting generators are very smaller in size and weight when compared with conventional generators. The low loss superconducting coil is rotated in an extremely strong magnetic field. Motors with very high powers could be constructed at very low voltage as low as 450V. this is the basis of new generation of energy saving power systems.

2. Low loss transmission lines and transformers : Since the resistance is almost zero at superconducting phase, the power loss during transmission is negligible. Hence electric cables are designed with superconducting wires. If superconductors are used for winding of a transformer, the power losses will be very small.

3. Magnetic Levitation : Diamagnetic property of a superconductor ie , rejection of magnetic flux lines is the basis of magnetic levitation. A superconducting material can be suspended in air against the repulsive force from a permanent magnet. This magnetic levitation effect can be used for high speed transportation.

4. Generation of high Magnetic fields : superconducting materials are used for producing very high magnetic fields of the order of 50Tesla. To generate such a high field, power consumed is only 10kW whereas in conventional method for such a high field power generator consumption is about 3MW. Moreover in conventional method ,cooling of copper solenoid by water circulation is required to avoid burning of coil due to Joule heating.

5. Fast electrical switching :A superconductor possesses two states , the superconducting and normal. The application of a magnetic field greater than H_c can initiate a change from superconducting to normal and removal of field reverses the process. This principle is applied in development of switching element cryotron. Using such superconducting elements, one can develop extremely fast large scale computers.

6. Logic and storage function in computers : they are used to perform logic and storage functions in computers. The current – voltage characteristics associated with Josephson junction are suitable for memory elements.

7. SQUIDS (superconducting Quantum Interference Devices) : It is a double junction quantum interferometer. Two Josephson junctions mounted on a superconducting ring forms this interferometer. The SQUIDS are based on the flux quantization in a superconducting ring. Very minute magnetic signals are detected by these SQUID sensors. These are used to study tiny magnetic signals from the brain and heart. SQUID magnetometers are used to detect the paramagnetic response in the liver. This gives the information of iron held in the liver of the body accurately.

Questions:

1. Describe how polarization occurs in a dielectric material.
2. Define dielectric constant of a material.
3. Explain the origin of different kinds of polarization.
4. Describe in brief various types of polarization.
5. Obtain an expression for the internal field.
6. Derive Clausius - Mossotti equation.
7. Describe the frequency dependence of dielectric constant.
8. Write note on Dielectric loss.
9. Explain the properties of ferroelectric materials.
10. What is piezoelectricity?
11. Distinguish between dia, para, ferro, antiferro,and ferromagnetic materials.
12. what is meant by Neel temperature
13. Define magnetization and show that $B = \mu_0 (H + M)$.
14. Explain the origin of magnetic moment.
15. Decribe the domain theory of ferromagnetism.
16. What is Bhor Magneton.
17. Draw and explain the hysteresis curve.
18. Discuss the characteristic features of soft and hard magnetic materials.
19. What are the applications of soft and hard magnetic materials?