UNIT-IV

Magnetic and Superconducting materials

Magnetic Materials

Origin of Magnetic Moment-Bohr Magneton. Ferromagnetic domain, Magnetization process by using domain, B-H curve explanation based on Domain theory and important outcomes of the curve. Hard and Soft Magnetic Materials.

Superconducting Materials

General properties of Superconductors. Effect of Magnetic Field, Critical current density, Meissner effect, Penetration depth. Type-I and Type-II superconductors, BCS theory, Magnetic levitation.

Introduction

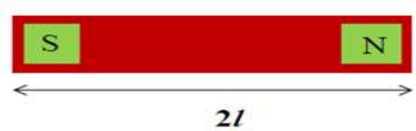
Magnetism arises from the Magnetic Moments or Magnetic dipoles of Magnetic Materials.

- When the electrons revolve around the nucleus Orbital magnetic moment arises, similarly when the electron spins, spin Magnetic moment arises.
- The permanent Magnetic Moments can arise due to
  - **The orbital magnetic moment of the electrons**
  - **The spin magnetic moment of the electrons, and**
  - **The spin magnetic moment of the nucleus.**

Note: Magnetic moment due to nucleus spin is very small compared to other two, hence can be neglected.

Magnetic Dipole:

It is system consisting of two equal and opposite magnetic poles separated by a finite distance(**2*l***).



Magnetic Moment:

It is defined as the product of its pole strength(**m**) and distance between the two poles.

i.e., Magnetic moment of a dipole =$2lm$

Units: ***ampere-meter²***

Magnetic dipole may arises when current flows in a conducting wire. In this case, the magnetic moment is defined as the product of current passing through the wire and cross section area of the wire.

i.e., Magnetic moment **=iA** , **Units:** ***ampere-meter²***

Note: *It is a vector quantity pointing from south to north pole.*

Magnetic Induction or Magnetic flux Density(B):

The number of lines of magnetic force (or) flux passing through unit area perpendicularly is known as Magnetic Induction.

$B = \Phi/A$ = Magnetic Flux/area

Units: wb/m^2 or **Tesla**.

<u>Magnetic field intensity</u> (H):

The force experienced by a unit north pole placed at a point in a Magnetic Field is known as Magnetic field strength (or) Magnetic Field Intensity.

Units : A/m

<u>Permeability</u>(μ):

The permeability (**μ**) is a measure of the amount of magnetic lines of forces penetrating through a material.

The Magnetic induction **B** is proportional to the applied Magnetic field intensity **H**, i.e.,

$$\boxed{\begin{aligned} &B \alpha H \\ &B = \mu H \\ &\mu = \frac{B}{H} \end{aligned}}$$

Where **μ** is permeability of a medium and is measured in **Henry per meter.**

Hence, the magnetic permeability is defined as the ratio of the magnetic flux density to the applied magnetic field intensity.

- The permeability of free space(μ_0) has a value of $\mathbf{4\pi X10^{-7}Hm^{-1}}$

<u>Relative permeability</u> (μ_r):

The ratio of absolute permeability of a medium to that of permeability of free space is called relative permeability μ_r of the substance.

$$\boxed{\begin{aligned} &\mu_r = \frac{\mu}{\mu_0} \\ &\mu_r = \frac{B/H}{B_0/H} = \frac{B}{B_0} \end{aligned}}$$

<u>Magnetization</u>(*M* or *I*):

"Magnetization refers to the process of converting a non-magnetic material into a Magnetic material".

- The measure of the magnetization of a magnetized specimen is called intensity of magnetization. It is defined as the magnetic moment per unit volume.

<u>Magnetic Susceptibility</u>(χ_m):

The intensity of Magnetization (**M**) is directly related to the applied field magnetic field intensity (**H**)

$$\boxed{\begin{aligned} &M \alpha H \\ &M = \chi_m H \\ &\text{magnetic susceptibility} \quad \chi_m = \frac{M}{H} \end{aligned}}$$

Note: *which produces the magnetization and **It has no units.***

Relation between the susceptibility(χ_m) and Relative permeability(μ_r):

When a magnetic material of cross-sectional area(**A**) and relative permeability (**μ_r**), is placed in a uniform field **H**, two types of lines of induction pass through it, one due to the magnetizing field **H** and other due to the material it self being magnetized by induction(**M**).

Thus the total flux density **B** will be given by

$$B = \mu_0 H + \mu_0 M$$
$$B = \mu_0 (H + M)$$

where μ_0 is the permeability of free space

$$\mu_0 = \frac{B}{(H+M)}$$

But relative permeability $\mu_r = \dfrac{\mu}{\mu_0}$

$$\mu_r = \frac{B/H}{B/(H+M)}$$
$$\mu_r = \frac{H+M}{H}$$
$$\mu_r = 1 + \frac{M}{H}$$
$$\mu_r = 1 + \chi_m \quad (\because \chi_m = \text{M/H})$$

Note: ***For non-magnetic substance susceptibility is zero & relative permeability is unity.***

Problems:

1). The magnetic field in the interior of certain solenoid has the value of **6.5×10^{-4} T**, when the solenoid is empty. When it is filled with iron, the field becomes **1.4T**. Find the relative permeability of iron.

(**Hint: χ_m=M/H χ_m= 2153.84 $\mu_r=1+\chi_m$.**
Ans: μ_r= 2154.84) ((or) μ_r=1+(M/H))

2). Find the relative permeability of a ferromagnetic material if a field of strength 220 amp/meter produces a magnetization 3300 amp/meter in it.

(**Hint: μ_r=1+(M/H) Ans: μ_r= 16**)

3). The magnetic field intensity in a piece of ferric oxide is **10^6 amp/meter**. If the susceptibility of the material is **1.5×10^{-3}**, calculate the magnetization of the material and the flux density.

(**Hint: χ_m=M/H ,M=χ_mH & B=μ_o (M+H)**
Ans: M=1.5×10^3A/m B= 1.257T)

4). A paramagnetic material has a magnetic field intensity of **10^4 amp/meter**. If the susceptibility of the material at room temperature is **3.7×10^{-3}**, calculate the magnetization and the flux density in the material.

(**Hint: χ_m=M/H ,M=χ_mH & B=μ_o (M+H)**
Ans: M=37A/m B= 0.0126T or wb/m^2)

Origin of Magnetic Moment:

The permanent magnetic moment in a material originates from the orbital motion and spinning motion of electrons in an atom.

Orbital Magnetic moment of the electron and Bohr Magneton:

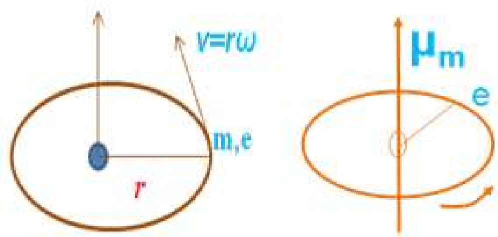
The orbital moment of an electron arises in principal because the electron in an orbit about the nucleus can be considered to be a small circulating current about the nucleus and this current produces a magnetic field.

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

The loop current produced by the electrons in an atom is given by

I=Charge of the electron/time = -e/T

where, '**T**' is time taken by the electron to make one revolution around the nucleus i.e., **T=2π/ω**



Therefore, **I = - eω/2π**

Where '**ω**' is angular velocity of the electron

As we know that the Magnetic moment is the product of magnitude of current and area of loop i.e.,

μ_m = (Current) (Area of loop)=I.A

$$\mu_m = -\frac{e\omega}{2\pi}(\pi r^2) = -\frac{e\omega r^2}{2}$$

$$\mu_m = -\frac{e}{2m}(m\omega r^2)$$

$$\mu_m = -(\frac{e}{2m})L \text{-----}(1)$$

where **L=mω*r*²** is the orbital angular momentum of electron.

The minus sign indicates that the magnetic moment **μ_m** is anti-parallel to the angular momentum '**L**'.

The possible orientation of the angular momentum vector when placed in an external magnetic field is given by

$$L_{l,B} = \frac{m_l h}{2\pi} \text{-----}(2)\ (\text{where, } m_l = \sqrt{l(l+1)}\ )$$

Combining equation (1) & (2),

$$\mu_m = -\left(\frac{e}{2m}\right)\frac{m_l h}{2\pi}$$

$$= -\left(\frac{eh}{4\pi m}\right)m_l$$

$$\mu_m = -\mu_B m_l = -\mu_B\sqrt{l(l+1)}$$

where $\boxed{\mu_B = \left(\frac{eh}{4\pi m}\right) = 9.27\times10^{-24}\, ampere - meter^2}$ is called Bohr Magneton.

Note: *Bohr Magneton is the accepted unit for measuring the magnetic moment of atomic systems.*

Spin Magnetic moment of the electrons:

Besides the orbital motion of an electron, it rotates about its own axes.

Substituting the value of magnetic spin angular momentum in equation (1), we get

$$\mu_s = -\left(\frac{e}{2m}\right)\frac{m_s h}{2\pi}$$

$$= -\frac{1}{2}\left(\frac{eh}{4\pi m}\right)$$

$$\mu_s = -\frac{\mu_B}{2} (\because m_s = \pm\frac{1}{2})$$

i.e., spin magnetic moment is half of a Bohr Magneton. **μ_s=9.4X10^{-24} A-m^2**.

Nuclear Spin Magnetic moment:

Similar to electrons, the protons present in nucleus possess spin, the vectorial sum of all the protons spin is equal to the nuclear spin.

The nuclear magnetic moment is expressed in the unit of nuclear Magneton is

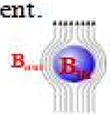
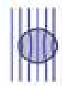
$$\mu_n = \frac{eh}{4\pi M_p} = 5.05\times10^{-27}\, A - m^2$$

Where **M_p** is the mass of the proton.

Classification of Magnetic Materials:

Based on different characteristics the magnetic materials are broadly classified into three types. i.e., Dia, Para & Ferro magnetic materials.Further ferro-magnetic materials are classified into ***Anti Ferro & Ferri Magnetic materials.***

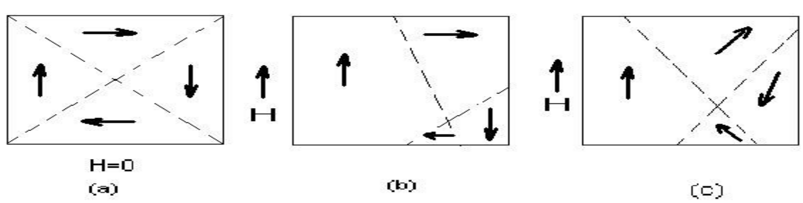
Brief comparison between the three magnetic materials

Diamagnetic	Paramagnetic	Ferromagnetic
• Feeble repulsion from the magnetic field	• Feeble attraction towards the magnetic field	• Strongly attracted towards the magnetic field.
• Permanent magnetic moment in each atom is zero.	• Possess Permanent magnetic moment in each atom.	• Possess enormous Permanent magnetic moment in each atom.
• χ is small but negative.	• χ is small but positive	• χ is large and positive .
• Independent of temperature.	• Obeys Curie law i.e., $\chi = C/T$	• χ decreases with temperature in complex manner. i.e., $\chi = C/(T-\theta)$.
• $\mu_r < 1$.	• $\mu_r > 1$.	• $\mu_r >>> 1$
• No spin alignment.	• Spin alignment is random.	• Spin alignment is in systematic. 
 • $B_{out} > B_{in}$	• $B_{out} < B_{in}$ 	• $B_{out} << B_{in}$
• Hysteresis is not exhibited.	• Hysteresis is not exhibited.	• Exhibit phenomenon of Hysteresis.
• Ex: Bi, Hg, Ag, Cu, Water air etc..	• Ex: Pt, Al, Chromium, Salts of Fe & Ni, Oxygen etc.	• Ex: Iron, steel, Cobalt, Nickel etc.

Domain theory of ferromagnetism:

According to Weiss, ferromagnetic material consists of a number of regions or domains, which are spontaneously magnetized.

- 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 of a random domain.



- **By motion of domain walls:** The volume of the domains that are favorably oriented with respect to the magnetizing field increases at the cost those that are unfavorably oriented.
- **By rotation of domains:** When the applied magnetic field is strong, rotation of the direction of magnetization occurs in the direction of field.

▪ In the process of domain growth, four types of energies are involved.

i) **Exchange energy:** It is the energy required in assembling the atomic magnets into a single domain and this work done is stored as potential energy.

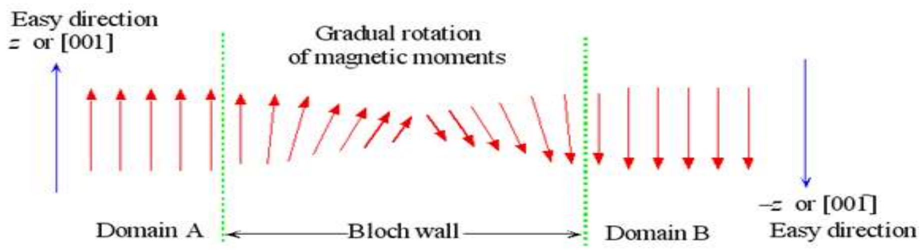
The volume of the domain may vary 10^{-2} to 10^{-6} cm^3.

ii) Anisotropy energy: In ferromagnetic crystals, energy of magnetization is found to be a function of crystal orientation. i.e., crystals have easy and hard directions of magnetization.

iii) Domain wall energy or the Bloch wall energy:

A thin region that separates adjacent domains magnetized in different directions is called domain wall or Bloch wall.

Thickness the Bloch walls are about 200 to 300 lattice constant.



iv) Magnetostriction energy:

The change in the dimension of a ferromagnetic material when it is magnetized is known as Magnetostriction.

Magnetostriction energy is the energy due to the mechanical stresses generated by domain rotation.

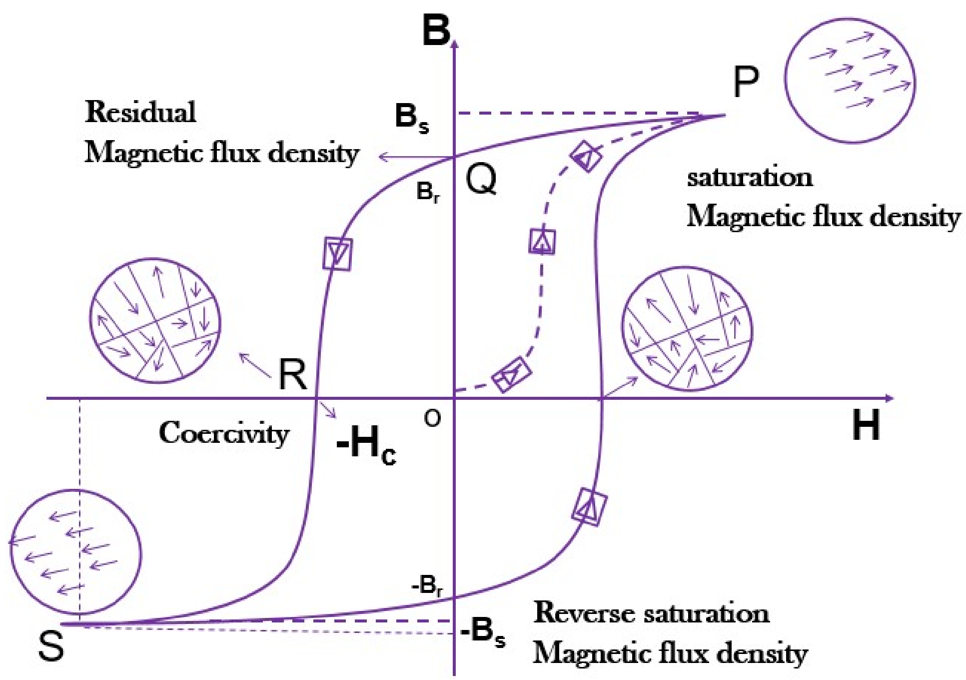
Magnetostriction effect is used in generation of ultrasonic waves

Hysteresis

The striking property of Ferro Magnetic materials is the relation between Magnetization and the strength of Magnetic field. This property is called Hysteresis.

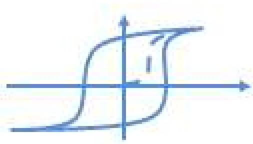
OR

The lagging of Magnetization behind the applied magnetic field is called the Hysteresis.



Explanation to Hysteresis Loop :

- If we start with no Magnetic flux density of specimen (**B=0**) with the increasing values of magnetizing field H.
- The Flux density of the specimen increases from zero to higher values and attains its maximum value at a point P, at this point the Magnetic flux density referred as Saturation Magnetic flux density.
- When we increase Magnetic field **H** there is no further increment in Magnetic moment.
- When we decrease Magnetic field **H to Zero**, the Magnetic flux density **B** attains point **Q**.
- At this point Magnetic flux density referred as **Residual Magnetic Flux Density B_r**.
- Further if we increase the Magnetic field from zero to negative values, the Magnetic flux density of material becomes zero at a point **R**, at that point the Magnetic field **$-H_c$** is referred as Coercivity of the specimen.
- If we increase Magnetic field H in reverse direction Magnetic flux density of material reaches its peak value at a points **S**.
- On reversing the polarities of Magnetic field and increasing its strength the Magnetic flux density slowly decreases first to residual value then to zero and finally increases to saturation state and touches the original saturation curve.
- The area of loop indicates the amount of energy wasted in one cycle of operation.

<table>
<tr><th colspan="2">Brief comparison between Hard and Soft magnetic materials</th></tr>
<tr><th>HARD MAGNETIC MATERIALS</th><th>SOFT MAGNETIC MATERIALS</th></tr>
<tr><td>• large hysteresis loss due to large hysteresis loop area.
• The hysteresis curve is thick and flat for hard magnetic materials.

• The coercivity and retentivity are large hence these materials cannot be easily magnetized and demagnetized.
• These materials have small values of permeability and susceptibility.
• These are used to make permanent magnets.
Ex. Alnico, Co, Ni, Fe, Dy, Gd etc.,
Application:
•These are used in magnetic detectors, microphones, flux meters, voltage regulators, damping devices and magnetic separators.</td><td>• low hysteresis loss due to small hysteresis loop area.
• The curve is tall and thin.

• The coercivity and retentivity are small, hence these materials can be easily magnetized and demagnetized.
• These materials have large values of permeability and susceptibility.
• These are used to make electromagnets.
Ex: Iron silicon alloys, Ferrous nickel alloy, soft iron etc.,
Application:
These are mainly used in electro-magnetic machinery and transformer cores and also used in switching circuits , microwave isolators and matrix storage of computers.</td></tr>
</table>

Superconductivity

Superconductivity was first discovered in 1911 by the Dutch physicist,Heike Kammerlingh Onnes.

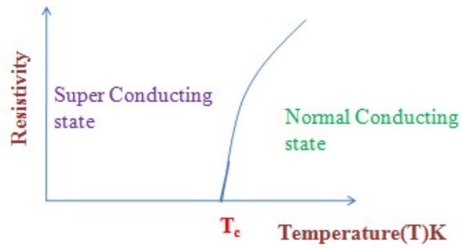
"Certain metals and alloys exhibit almost zero resistivity (infinite conductivity) when they are cooled to sufficiently low temperatures. This phenomenon is called **Superconductivity**".

General Properties of Superconductors:

1. TRANSITION TEMPERATURE: The temperature at which a normal substance changes to a superconducting substance and vice-versa is called the critical temperature (T_c) or the transition temperature.

Different materials have different transition temperature(T_c) values.

Hg, T_c =4.2K; Lead, T_c =1.19K; Tungsten, T_c =0.01K; Tin ,T_c =0.39K; Cadmium T_c =0.55K etc..

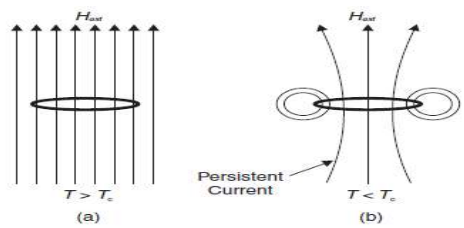


2). **Critical magnetic field (Hc)**

The state of superconductivity that exists for a given magnetic field at a given temperature is called critical magnetic field.

3).**Effect Of Current:**

When an electric current is set up in a superconductor, it can persist for a long time even without any emf. Due to the presence of the persistent current, a superconductor also produces a magnetic field.



4).**Isotopic Effect:** The phenomenon of decrease of critical temperature with increasing atomic mass is called isotopic effect.

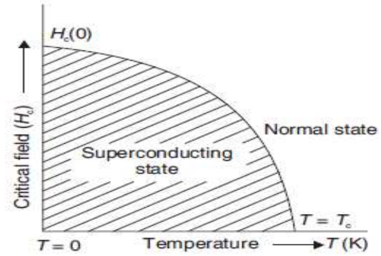
$$T_c \propto \frac{1}{\sqrt{M}}$$

$$T_c M^{1/2} = \text{constant}$$

5).**Specific Heat,** 6).**Cooper Pair Of Electrons,** 7).**Energy Band Gap**

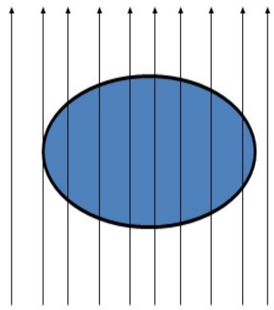
Note: The dependence of the temperature on the magnetic field can be represented by

$$H_c = H_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]$$

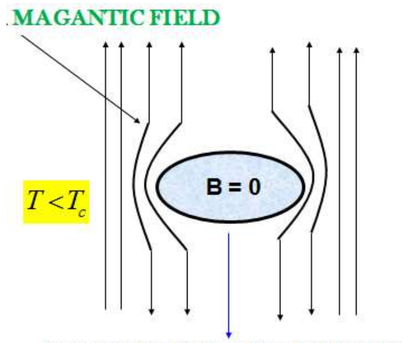


Meissner Effect:

When a weak Magnetic field is applied to a superconducting specimen at a temperature T_c , the magnetic flux lines are expelled & the specimen acts as an ideal Dia magnet. This effect is called Meissner effect.



Normal Conduction in a Magnetic Field as $T>T_c$ or $H>H_c$



PER FECT DIAMAGNATIC MATIRIAL OR SUPER CONDUCTING MATERIAL

$$B=\mu_0(H+M)$$
$$B=0$$
$$0=\mu_0(H+M)$$
$$H+M=0$$
$$H=-M$$
$$\frac{M}{H}=-1$$
$$\chi=-1$$

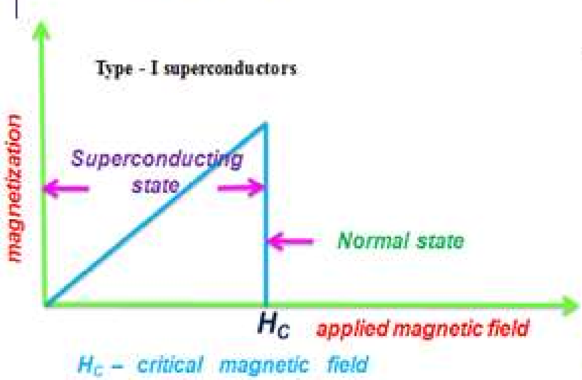
Types of superconductors

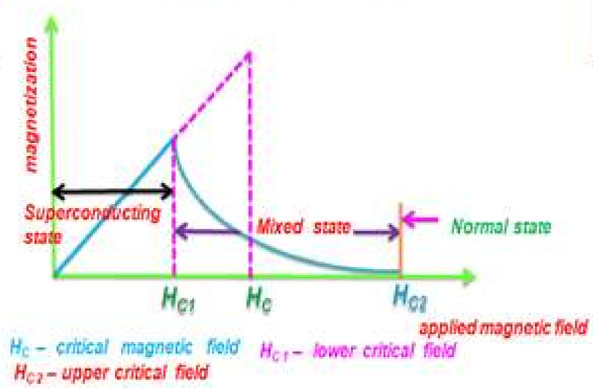
Based on diamagnetic response superconductors can be classified as

1) Type - I superconductors (or) Soft superconductors
2) Type - II superconductors (or) Hard superconductors

Comparison between Type-I & Type-II Superconductors

Type –I Superconductors	Type –II Superconductors
• They exhibit complete Meissner effect	• They do not exhibit complete Meissner effect
• They show perfect diamagnetic behavior	• They do not show perfect diamagnetic behavior
• They have only one critical magnetic field, H_c	• They have two critical magnetic fields, lower critical magnetic field H_{c1} and Upper critical magnetic field H_{c2}
• There is no mixed state or intermediate state in case of these materials.	• Mixed state or intermediate state is present in these materials(***Vortex-region***)
• The material loses magnetization abruptly	• The material loses magnetization gradually
• Highest value for H_c is about 0.1 Wb/m^2	• Upper critical filed is of the order of 30 Wb/m^2
• They are Soft superconductors	• They are Hard superconductors
• Ex: Al, Zn, Hg ,Sn etc	• Ex: Nb-Sn, Nb-Ti, Nb-Zr etc





Penetration depth:

When a superconductor is placed in a week external field H, the field penetrates the superconductor for only a short distance λ called London penetration depth. After which it decays rapidly to zero.

Where m is the mass of the electron, q is the charge and n is the density of electrons

Typical values of λ_L range from 50 to 500 nm.

Critical current density:

The maximum current density at which the superconductivity disappears is called the critical current density.

Note:An electrical current in a wire creates a magnetic field around the wire.

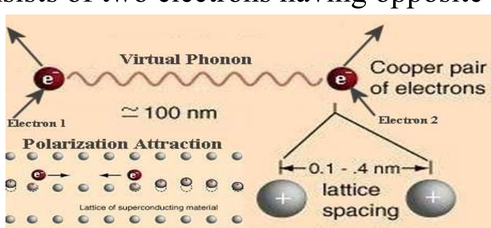
The strength of the magnetic field increases as the current in the wire increases.

Because superconductors are able to carry large currents without loss of energy, they are well suited for making strong electromagnets.

Introduction to BCS theory of Superconductivity:

A theory of superconductivity formulated by John Bardeen, Leon Cooper, and Robert Schrieffer. It explains the phenomenon in which a current of electron pairs flows without resistance in certain materials at low temperatures. This can happen, so the theory says, when a single negatively charged electron slightly distorts the lattice of atoms in the superconductor, drawing toward it a small excess of positive charge. This excess, in turn, attracts a second electron. It is this weak, indirect attraction that binds the electrons together, into a Cooper pair.

- A pair of free electrons coupled through a phonon is called a *Cooper pair.*
- *Each Cooper* pair consists of two electrons having opposite moments and opposite spins.



.

Dr. Maheshwar Reddy Mettu
Asst. Professor of Physics
Sreenidhi Institute of Science and Technology