MODULE - IV

MAGNETIC AND SUPERCONDUCTING PROPERTIES

Magnetic and Superconducting Properties :

Permeability, field intensity, magnetic field induction, magnetization, magnetic susceptibility, origin of magnetic moment, Bohr magneton, classification of dia, para and ferro magnetic materials on the basis of magnetic moment, domain theory of ferro magnetism on the basis of hysteresis curve, soft and hard magnetic materials.

Superconductivity:

General properties, Meissner effect, effect of magnetic field, type-I & type-II superconductors, BCS theory, applications of superconductors.

Magnetic Materials –Basic Definitions

- **Magnetic dipole**
- The system in which two equal and opposite magnetic poles separated by a distance is called magnetic dipole. This magnetic dipole produces magnetic moment depending on the alignment with respect to the applied magnetic field.
- **Magnetic flux (Φ)**
- It is defined as the amount of magnetic lines of forces passing through a point. It is denoted by '**Φ**'
- **Φ** = AB

Where A= Area of cross section of the material in m^2

- B = magnetic Induction in Wb/ m^2
- Units: Weber (Wb)

Magnetic Materials –Basic Definitions

- **Intensity of Magnetization (M)**
- When a material is magnetized, it develops a net magnetic moment. The magnetic moment per unit volume is called Intensity of magnetization
- Magnetization (M) $= \frac{\text{Magnetic moment}}{\text{Volume}}$
- Units: Amp/m
- **Magnetic Induction (B)**
- Magnetic induction or Magnetic flux density at a point is defined as the number of lines of force through unit area of cross-section perpendicularly. It is denoted by 'B'. It is
- i.e. $B = \frac{\Phi}{A}$ weber / m^2
-

Magnetic Materials –Basic Definitions

- **Magnetizing field strength (H)**
- The magnetic field strength H at any point is the force experienced by a unit North pole placed at that point. Units for H: Amp /m.
- The magnetic flux density generated is proportional to the magnetic field strength. i.e. $B \propto H = B = \mu H$

Where μ = absolute permeability of the medium.

If the medium is air or vacuum $B=\mu_0 H$

$\mu_{0=}$permeability of free space i.e. air or vacuum $\mu_0 = 4\pi \times 10^{-7}$ H/m

Magnetic Materials –Basic Definitions

Permeability (μ)

It indicates, with which the material allows magnetic lines of force to pass through it.

Or

It is the ability of the medium to pass magnetic lines of forces through it.

- There are three Permeabilities i.e. μ, μ_0, μ_r
- $\mu = \mu_0 \mu_r$

Where μ = Absolute permeability of the medium

μ_0 = Permeability of free space i.e. air or vaccum

- μ_r = Relative permeability of the medium

Magnetic Materials –Basic Definitions

- **Magnetic moment or Magnetic Dipole Moment**
- The magnetic moment is the product of pole strength and magnetic length.
- Magnetic moment μ_m = (current) × (area of circulating orbit)μ_m = (I) × (πr^2)
- Units: Amp-m^2
- When the magnetic dipoles (atoms consisting of charged particles like protons & neutrons) undergo orbital motion (or) spin motion produces a magnetic moment. Since motion of charged particles is considered as closed electric current loops this in turn produces magnetic moment.

Magnetic Materials –Basic Definitions

- **Magnetic susceptibility (χ)**
- If H is the applied magnetizing field intensity and M is the amount of magnetization of the material, then $\chi = \frac{M}{H}$
- $\chi = 0$ in vacuum
- $\chi = +ve$ for paramagnetic and Ferro magnetic materials
- $\chi = -ve$ for diamagnetic materials
- Units: It has no units.

- **Relation between B, H, M**
- When a material is kept in a magnetic field, two types of induction arise; due to the magnetizing field H and the other as a consequence of the magnetization, M of the material itself. The magnetic induction, B, produced inside the material is given by
- $B = \mu_0(H + M)$--------> (1)
- We know that B = μH

But $\mu = \mu_0\mu_r$ $B = \mu_0 \mu_r H$ --------> (2)

from (1) $B = \mu_0(H + \chi H)$ =

- $B = \mu_0(1 + \chi)H$ --------> (3)

Comparing (2) and (3) $\mu_r = 1 + \chi$

ORIGIN OF MAGNETIC MOMENT

- In atoms, the permanent magnetic moment arises due to
- Orbital motion of electrons
- The spin of electrons
- The spin of nucleus

Magnetic moment due to orbital motion of the electrons (μ_l)

- Let us consider an electron of charge 'e' revolving around a nucleus in time period 'T' in a circular orbit of radius 'r'. Then a magnitude of circular current 'I' is given by
- $$\mathrm{I} = \frac{Charge}{Time} = \frac{e}{T} \rightarrow (1)$$

$$\text{But} \qquad \mathrm{T} = \frac{2\pi}{\omega}$$

ORIGIN OF MAGNETIC MOMENT

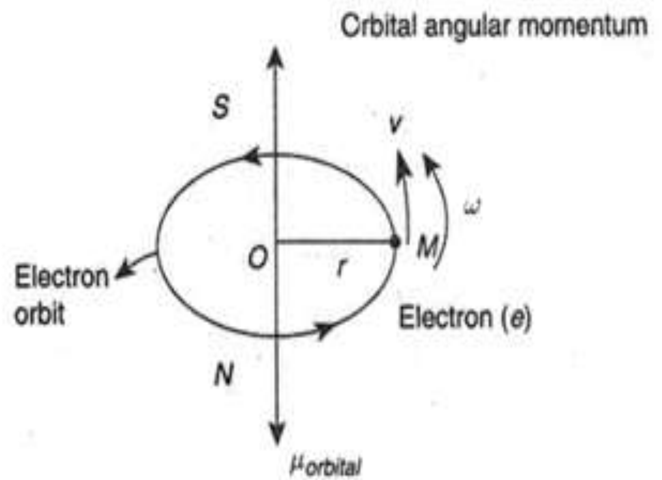
- Where ω = angular velocity of electron
- $I = \frac{e\omega}{2\pi}$
- But magnetic moment of electron is $\mu_l = \times A$

μ_l = current area of circulating orbit

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

We know that angular momentum of any particle, L = mωr^2-------- (3)

$$\frac{L}{m} = \omega r^2 \text{------}(4)$$



Orbital magnetic moment of electrons

ORIGIN OF MAGNETIC MOMENT

Substituting eq.(4) in eq.(2) we get

Orbital magnetic moment, $\mu_l = (-\frac{e}{2m}).L \rightarrow (5)$

$\mu_l = \quad (-\frac{e}{2m})\ L$

- But from Bohr's atomic modelmvr=$\frac{nh}{2\pi}$
- L = $\frac{lh}{2\pi}$ Where l = orbital quantum number
- L = orbital angular momentum
- The values of l = 0, 1, 2---------- (n-1)

Hence $\mu_l = (-\frac{e}{2m})\ (\frac{lh}{2\pi}) = \ \mu_l = -\ (\frac{eh}{4\pi m})\ l \rightarrow (6)$

Where $\frac{eh}{4\pi m} = \mu_B$ is a constant called Bohr magneton and its value is 9.27×10^{-24}amp-m^2

- Hence eq(6) becomes $\mu_l = l\mu_B \quad \rightarrow (7)$
- ***Bohr magneton is the fundamental unit of magnetic moment.***

ORIGIN OF MAGNETIC MOMENT

- Spin magnetic moment $\mu_s = -2(\frac{e}{2m})\ S$ → (9)
- where S=spin angular momentum, e = charge of electron, m = mass of electron
- $S = \frac{sh}{2\pi}$

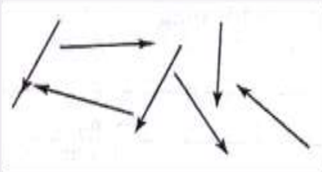
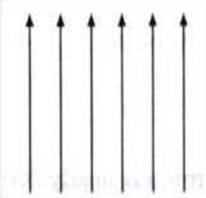
where S = spin quantum number, h = Planck's constant.

- *Spin magnetic moment of electrons*
- From equation (9), $\mu_s = -2(\frac{e}{2m})\ S$

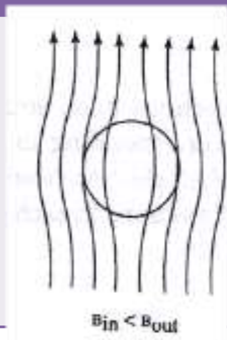
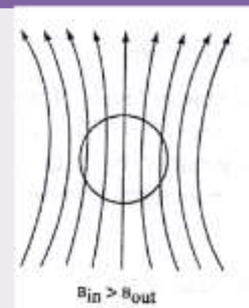
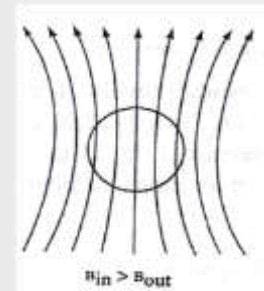
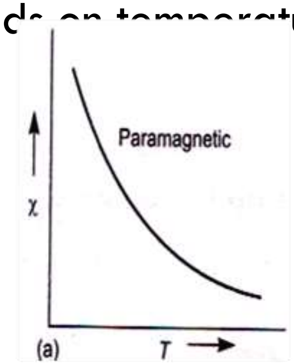
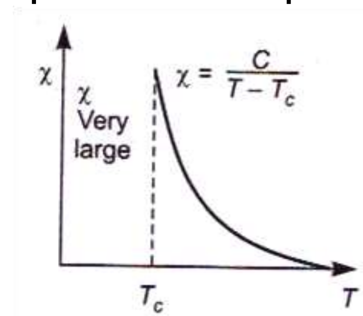
  Since $S = \frac{sh}{2\pi}$
- $\mu_s = -2(\frac{e}{2m})\ (\frac{sh}{2\pi})$
- $s = \pm\frac{1}{2}$, $\mu_s = \pm\ \frac{eh}{4\pi m}$
- $\mu_s = \frac{eh}{4\pi m}, -\frac{eh}{4\pi m}$ $\mu_s = +\mu_{\boldsymbol{B}}, -\ \mu_{\boldsymbol{B}}$
- *Hence spin magnetic moment of electron is equal to $\mu_{B.}$ That is one Bohr magneton*

- **Magnetic moment due to Nuclear spin or spin of all protons (μ_n)**
- The magnetic moment of the nucleus is given by $\mu_n = \frac{eh}{4\pi mp} \rightarrow (10)$
- Where m_p= mass of proton
- The constant $\frac{eh}{4\pi mp}$ is called nuclear magneton.
- The value of nuclear magneton $\frac{eh}{4\pi mp}$=5x10^{-27}A-m^2
- This is small when compared to Bohr magneton.

CLASSIFICATION OF MAGNETIC MATERIALS

Diamagnetic materials	Paramagnetic materials	Ferromagnetic materials
1.Diamagnetism: It is the property of the material which has repulsive nature (or) opposing magnetization.	1.Paramagnetism: It is the property of the material which has weak attractive force.	1.Ferromagnetism It is property of the material which has strong attractive force.
2. The property is due to orbital motion of electrons.	2. The property is due to spin of electrons.	2. The property is due to spin of electrons.
3. There is no spin	3. Spin is random 	3. Spin is parallel 
4. These materials are lack of magnetic dipoles.	4. These materials have permanent dipoles.	4. They have permanent magnetic dipoles.
5. They do not possess permanent dipole magnetic moment (it is zero). Hence spontaneous magnetization is zero.	5. They possess permanent magnetic dipole moment. But there is no spontaneous magnetization in the absence of external field, due to random spin.	5. They possess permanent magnetic dipole moment. Also in the absence of field they have spontaneous magnetization even in the absence of external field due to parallel spin.

CLASSIFICATION OF MAGNETIC MATERIALS

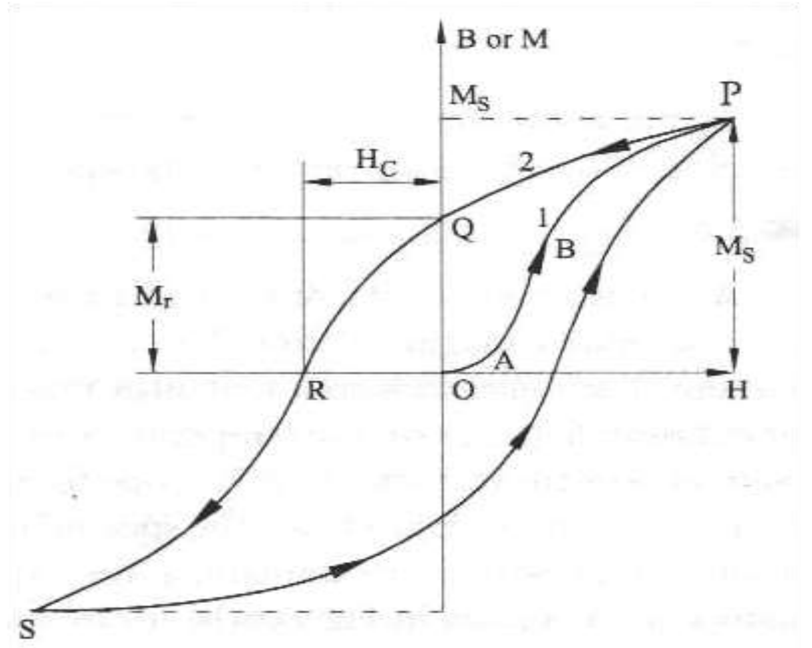
Diamagnetic materials	Paramagnetic materials	Ferromagnetic materials
6. 	6. 	6. 
7. The relative permeability $\mu_r<1$.	7. The relative permeability $\mu_r>1$.	7. The relative permeability $\mu_r>>1$.
8.Susceptibility χ is small and negative	8. Susceptibility is small but positive	8. Susceptibility is large and positive
9. χ does not depend on temperature. No particular is graph is drawn.	9. χ depends on temperature 	9. χ depends on temperature 

Diamagnetic materials	Paramagnetic materials	Ferromagnetic materials
10. χ does not depend on temperature.	10. $\chi = c/T$ (curie law) C=curie constant T = absolute temperature	10. $\chi = c/T\text{-}\theta$ curie-Weiss law θ = curie temperature
11. Do not exhibit phenomenon of hysteresis	11. Do not exhibit phenomenon of hysteresis	11. Exhibit phenomenon of hysteresis
11.Examples Cu, Au, Zn, H_20, Bi etc. organic materials.	11.Examples: Al, Pt, Mn,CuCl2 etc. Alkali & transition metals.	11.Examples: Fe, Ni, Co, MnO, $Fe_2\ 0_3$, Zn ferrite, Ni ferrite, Mn ferrite

FERROMAGNETIC MATERIAL-HYSTERESIS CURVE

Hysteresis means the lagging of magnetization "B" behind the applied magnetizing field "H". The energy supplied to the specimen during magnetization is not fully used. The balance of energy left in the material is produced as heat i.e. loss of heat called" Hysteresis Loss".

This phenomenon of magnetic Hysteresis is an "Irreversible" characteristic of ferromagnetic material. The loop (or) area refers to the hysteresis loop. Hysteresis loss occurs in ferromagnetic materials below Curie temperature.

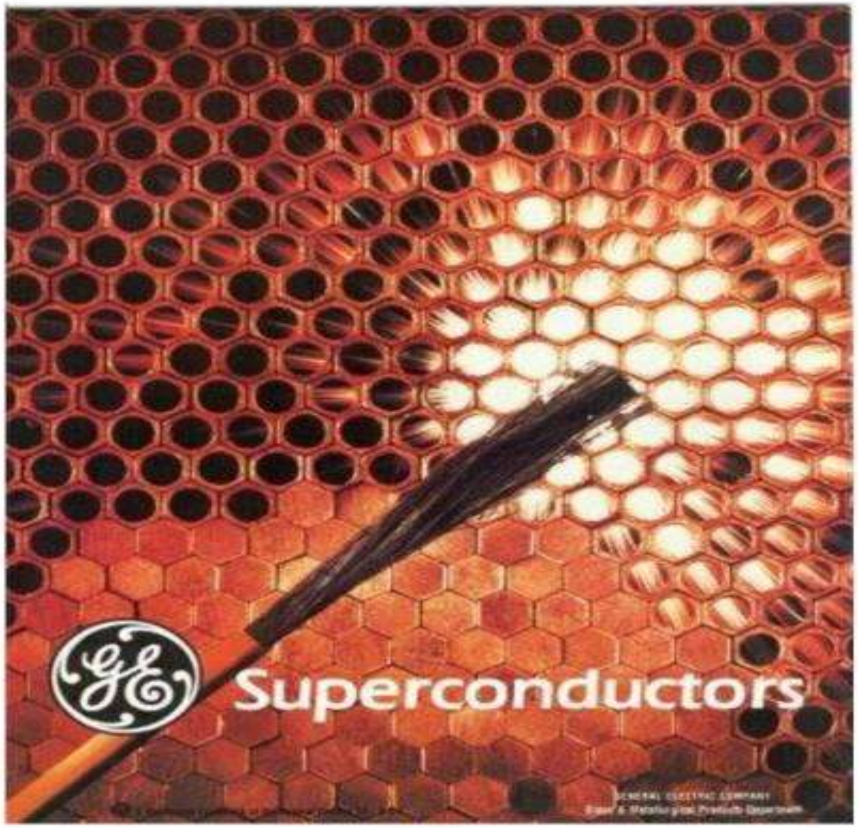



Thank you!

SUPERCONDUCTORS

- Superconductivity is a phenomenon in certain materials at extremely low temperatures, characterized by exactly zero electrical resistance and exclusion of the interior magnetic field (i.e. the Meissner effect)

- This phenomenon is nothing but losing the resistivity absolutely when cooled to sufficient low temperatures



WHY WAS IT FORMED ?

- Before the discovery of the superconductors it was thought that the electrical resistance of a conductor becomes zero only at absolute zero

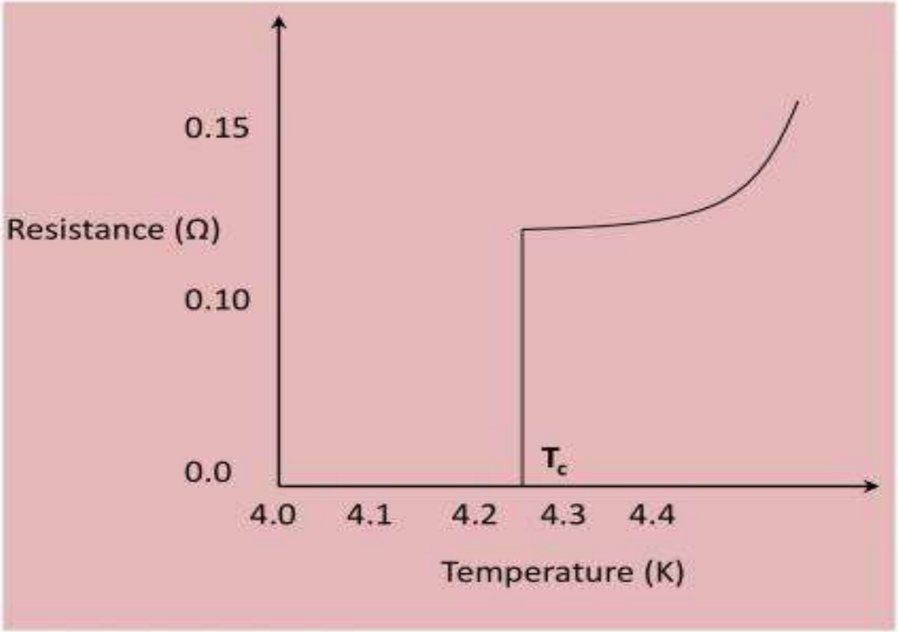
- But it was found that in some materials electrical resistance becomes zero when cooled to very low temperatures

- These materials are nothing but the <u>SUPER CONDUTORS.</u>

WHO FOUND IT?

- Superconductivity was discovered in 1911 by Heike Kammerlingh Onnes , who studied the resistance of solid mercury at cryogenic temperatures using the recently discovered liquid helium as 'refrigerant'.
- At the temperature of 4.2 K , he observed that the resistance abruptly disappears.
- For this discovery he got the NOBEL PRIZE in PHYSICS in 1913.
- In 1913 lead was found to super conduct at 7K.
- In 1941 niobium nitride was found to super conduct at 16K

H. Kammerlingh Onnes – 1911 – Pure Mercury



Effect of Magnetic Field

The superconducting state of the material cannot exist in presence of a magnetic field of critical value even at absolute zero temperature.

- Critical magnetic field (H_C) – Minimum magnetic field required to destroy the superconducting property at any temperature

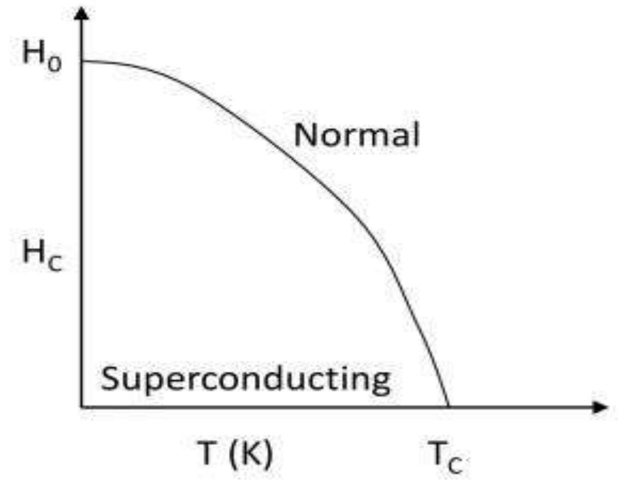
$$H_C = H_0\left[1-\left(\frac{T}{T_C}\right)^2\right]$$

H_0 – Critical field at 0K

T - Temperature below T_C

T_C - Transition Temperature

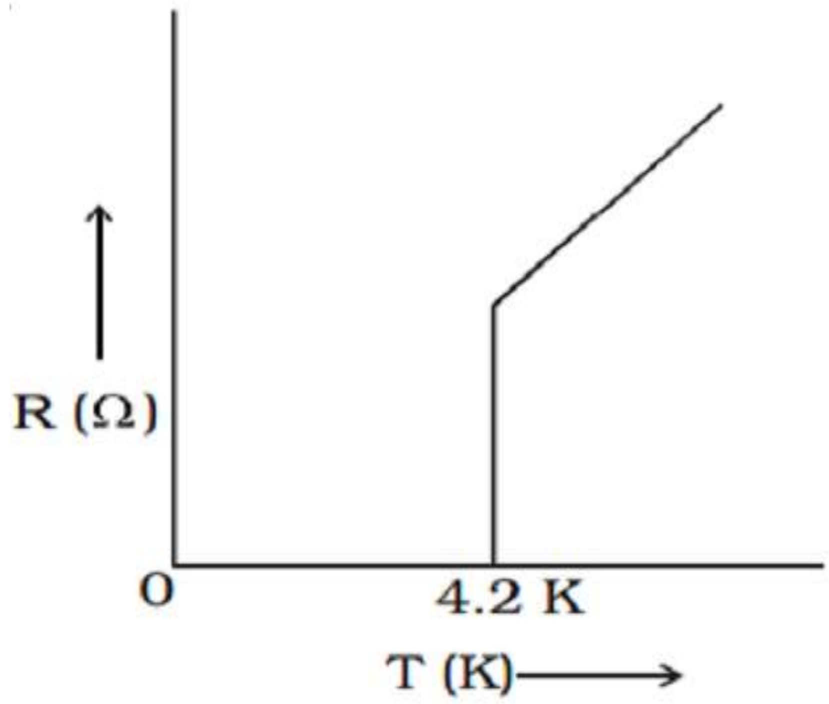
Element	H_C at 0K (mT)
Nb	198
Pb	80.3
Sn	30.9



INTRODUCTION TO SUPERCONDUCTIVITY

It was thought that the electrical resistance of a conductor becomes zero only at absolute zero temperature.

But in 1911, H. K. Onnes studied the properties of mercury at very low temperature using liquid helium and is found that the resistivity of mercury drops to zero at 4.2 K and changes into a superconducting material.

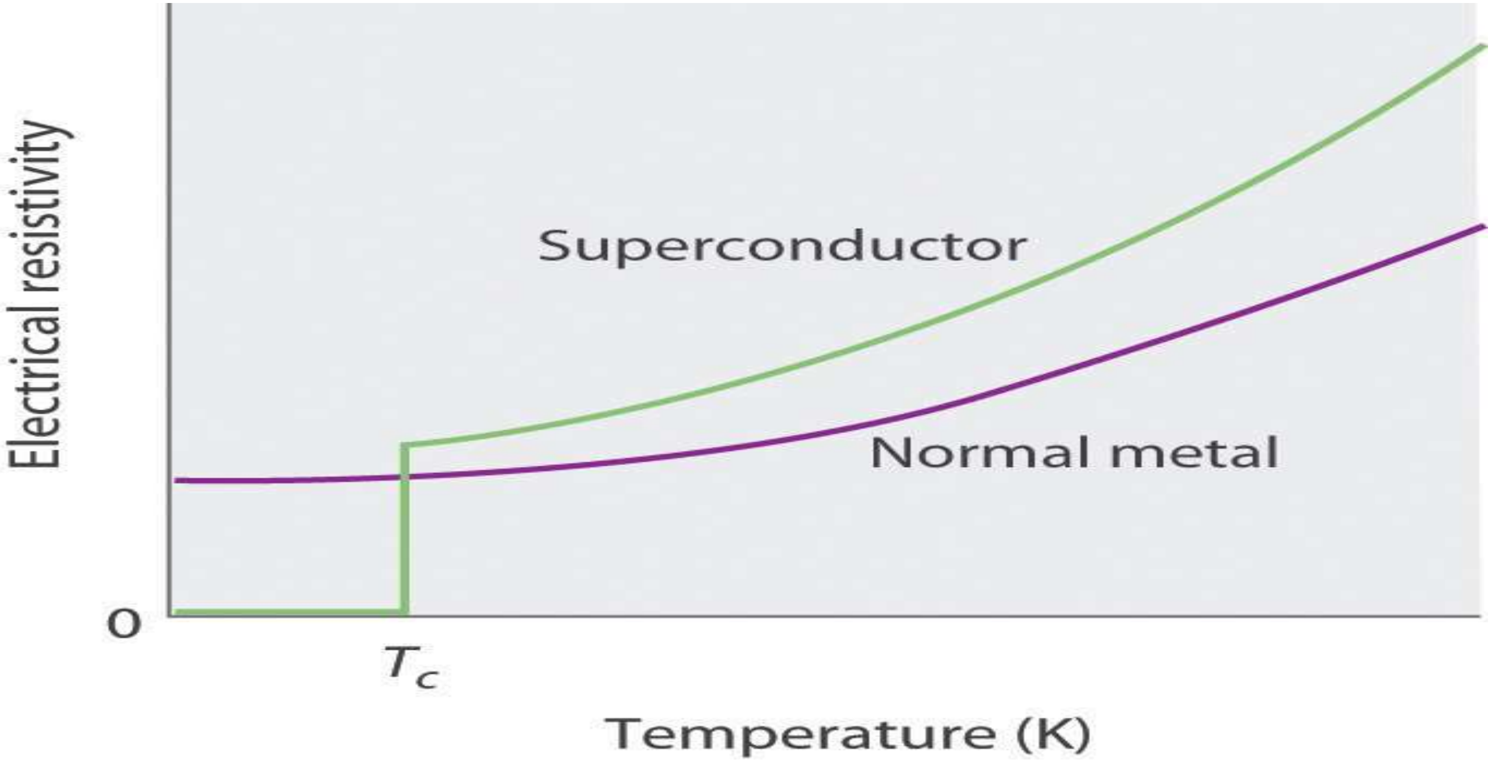


Superconductivity of mercury

Definition

The ability of certain metals and alloys exhibit almost zero electrical resistivity when they are cooled to low temperature is known as superconducting.

(i.e., maximum conductivity with zero resistance at zero Kelvin)



PROPERTIES OF SUPERCONDUCTORS:

At Critical temperature, the following properties are observed.

1. The electrical resistivity drops to zero.
2. The magnetic flux lines are excluded (ejected out) from the superconductors.
3. There is discontinuous change in the specific heat.
4. There are small changes in the thermal conductivity and volume of the materials

Properties of Superconductors

Superconductors exhibit many unusual and interesting properties

1. Zero Electrical Resistance

A superconductor is characterized by zero electrical resistivity.

A superconductor ring is taken in *normal state* and kept in a magnetic field and it is cooled to below the critical temperature so that it goes into the *superconducting state*.

When the external magnetic field is switched off, a current is induced in the ring.

If the ring had a finite resistance, R, the current circulating in the ring would decrease according to the equation,

$$I(t)=I(0)\exp(-Rt/L)$$

Where L is the inductance of the ring.

The decay current is monitored by a change in the magnetic flux through a test coil held close to the superconducting ring. Any change in the magnetic flux of the superconducting ring will induce an *emf* in the test coil.

Careful measurements established that the resistivity of superconductors could be taken as zero.

2. Persistent Current

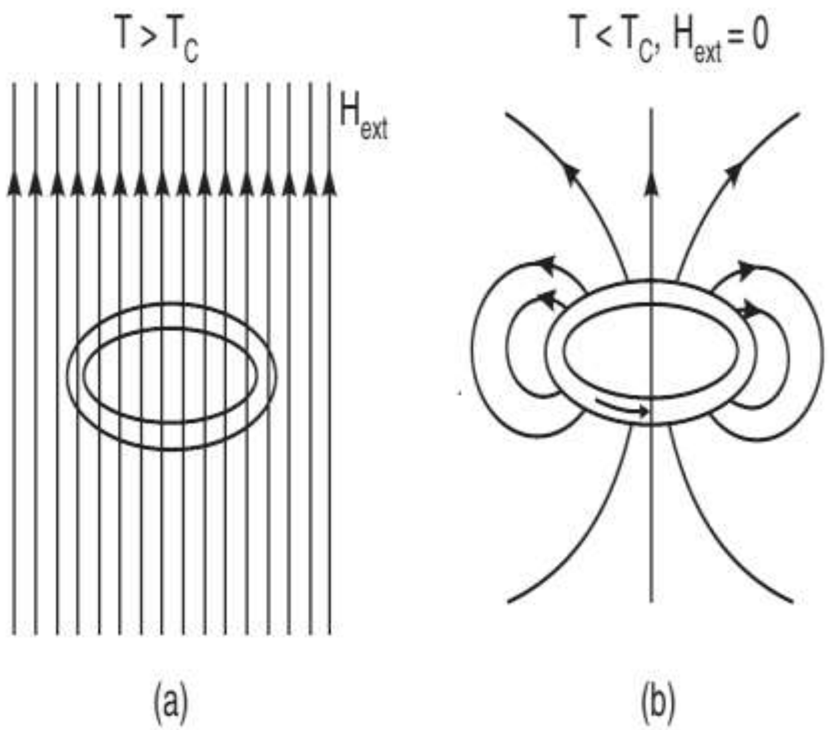
Once a current is started in a closed loop of superconducting material, it will continue to keep flowing, of its own accord, around the loop as long as the loop is held below the critical temperature (Fig.). Such a steady current, which flows without diminishing in strength, is called a **persistent current.**

The persistent current does not need external power to maintain it because there do not exist power $P = (I^2) R$ losses. Calculations show that once the current flow is initiated, it persists for more than 10^5 years.

Persistent current is one of the most important properties of a superconductor.

Superconductor coils with persistent current flowing through them produce magnetic fields and can therefore act as magnets.

Such a superconducting magnet does not require power supply to maintain its magnetic field.



3. CRITICAL TEMPERATURE (Tc) (or) TRANSITION TEMPERATURE

The temperature at which a normal conductor loses its resistivity and becomes a superconductor is known as critical temperature (or) Transition temperature.

Every superconductor has its own critical temperature at which it passes over into superconducting state.

Depending on the transition temperature, superconductors are classified into two groups are

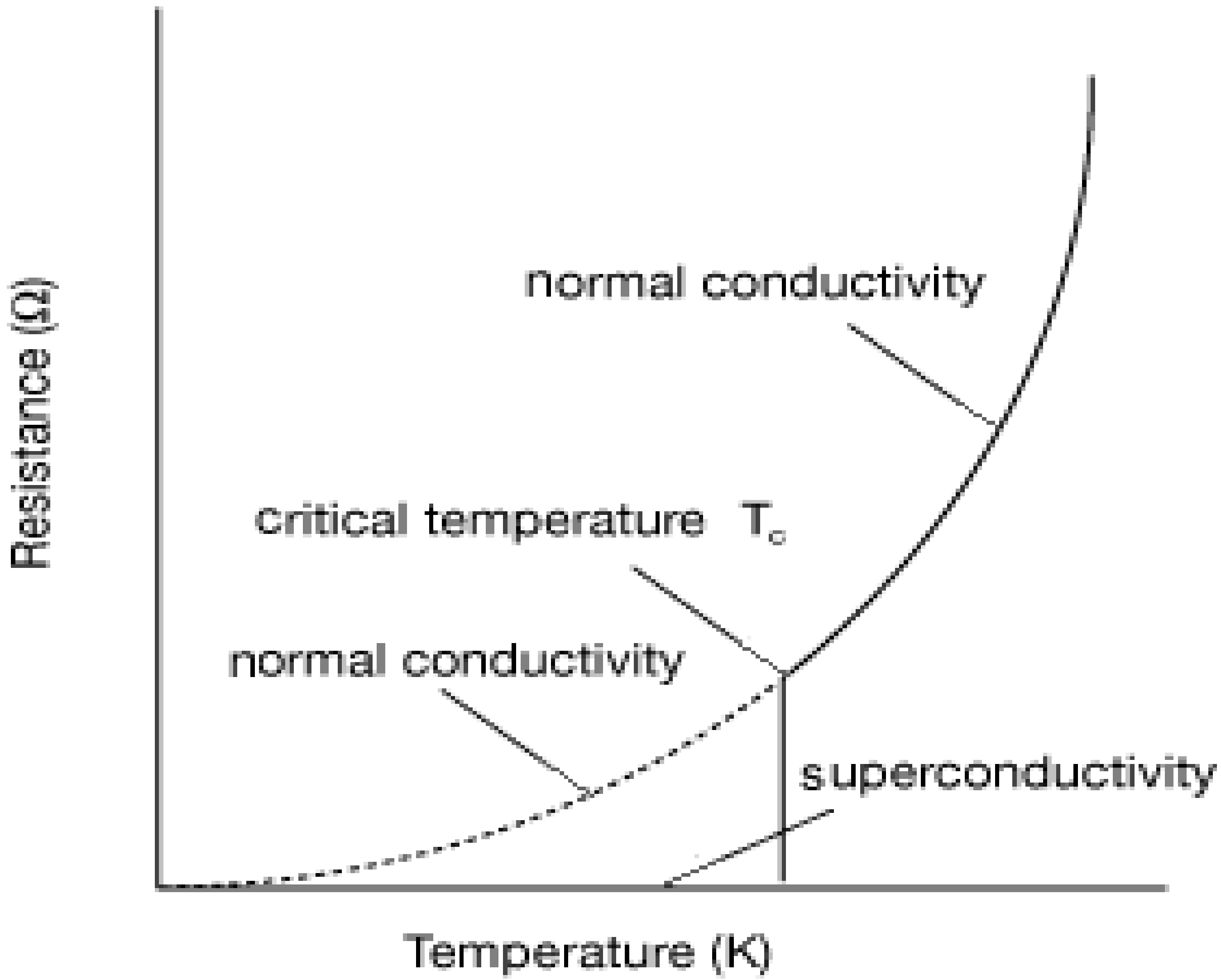
- Low temperature superconductors (LTS):The superconductors which have low transition temperature (below 30K) are known as low temperature superconductors.

Example: Tin (3.2 K), Mercury (4.15 K).

- High temperature superconductors (HTS): The superconductors which have high transition temperature (above 30K) is known as high temperature superconductors.

Example: Barium - Lanthanum - Copper - Oxide (BLCO) - 35 K Yttrium - Barium - Copper - Oxide - ($Y Ba_2 Cu_3O_4$) - 92 K

SUPERCONDUCTORS



4. Critical Magnetic Field

Superconducting state depends on the strength of the magnetic field in which the material is placed.

Superconductivity vanishes if a sufficiently strong magnetic field is applied. The minimum magnetic field, which is necessary to regain the normal resistivity, is called the **critical magnetic field, *Hc*.**

When the applied magnetic field exceeds the critical value *Hc*, the superconducting state is destroyed and the material goes into normal state.

The value of *Hc* varies with temperature. Figure shows the dependence of *Hc* on temperature in a superconductor.

At T< *Tc*, *in the absence of magnetic field*, the material is in superconducting state.

When a magnetic field, *H*, is applied and as its strength reaches the critical value *Hc*, *the superconductivity in the material disappears.*

At any temperature *T* <*Tc* the material remains superconducting until *H*=*Hc* is applied. When *H*>*Hc*, the critical value, the material goes into normal state.

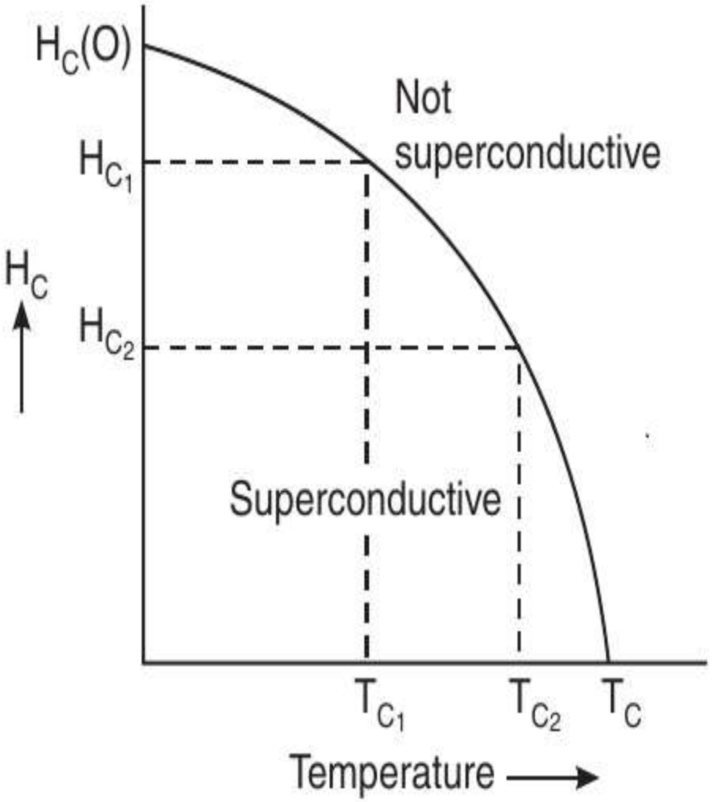


Fig: Schematic representation of the critical magnetic field as a function of temperature.

The critical field required to destroy the superconducting state decreases progressively with increasing temperature.

The dependence of critical field on temperature is governed by the following relation.

$$Hc(T)=Hc(0)[1-(T/Tc)^2],$$

where Hc(0) is the critical field at ***0k.***

5. Critical Current Density

The critical magnetic field required to destroy superconductivity need not be necessarily applied externally. An electric current flowing through the superconducting material itself may produce magnetic field of requisite strength.

Thus, if a superconducting ring carries a current *I, it gives rise to its own magnetic field. As the current increases to* ***a critical value, Ic****, the associated magnetic field increases to Hc and the superconductivity disappears*. The maximum current density at which the superconductivity disappears is called the **critical current density, *Jc*.**

For any value of $J < J_c$, the current can sustain itself whereas for values $J > J_c$, the current cannot sustain itself. This effect was observed in 1916 by Silsbee and is known as ***Silsbee effect.***

A superconducting ring of radius *R* ceases to be a superconductor when the current is,

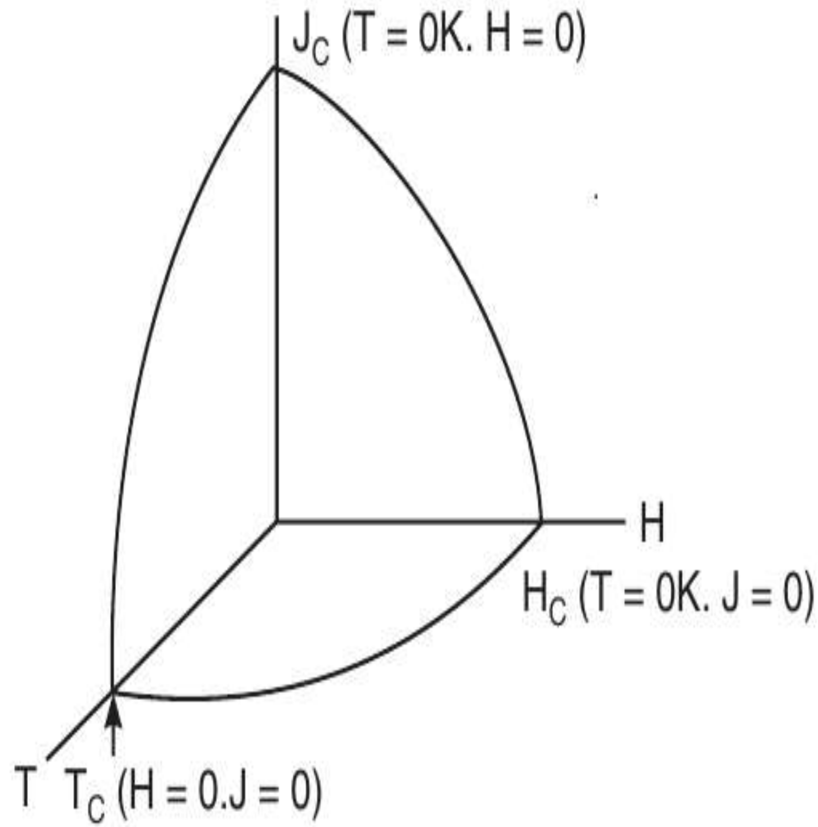
$$I_c = 2\pi R H_c$$

Thus, the existence of a critical current sets a definite limit to the size of the current that can flow through a superconducting coil without disturbing its superconducting state.

The maximum current that a superconductor can carry decreases as the temperature is raised and falls to zero at the transition temperature of the material.

Since the critical current falls with temperature, the critical magnetic field will also decrease as the transition temperature is approached.

The variation of **critical current density *Jc* *and critical* magnetic field *Hc*** with temperature is shown in Fig.



Meissner Effect:

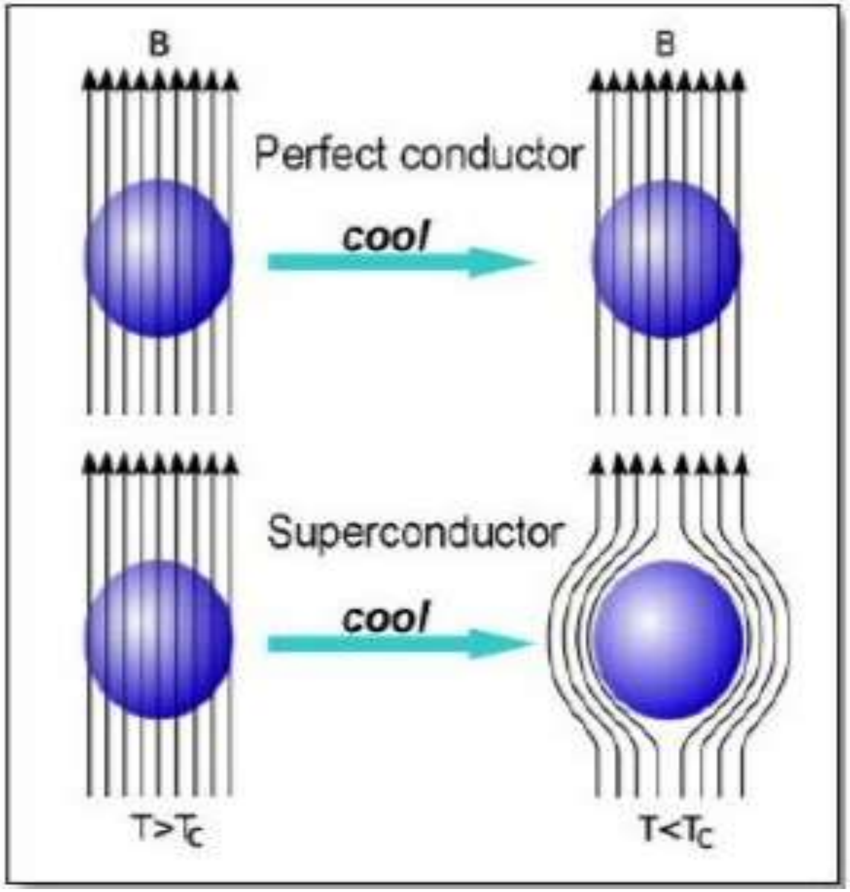
Meissner and Ochsenfeld in 1933 observed—

When a superconducting material at temp. $T > T_c$, is placed in ext. magnetic field, lines of magnetic induction pass through its body,

but when it is cooled below the critical temp. i.e., $T < T_c$, these lines of induction are pushed out of the superconducting body.

So, **inside the SC body B = 0**

This is known as **Meissner Effect**, which is the characteristic property of a superconductor



When superconductors are cooled below their critical temperature in the presence of a magnetic field, the magnetic flux is expelled from the interior of the specimen and the superconductor becomes a perfect diamagnetic. This phenomenon is known as **Meissner effect.**

TYPES OF SUPER CONDUCTORS

Superconductors are classified and as follows:

Based on the value of Hc we have,

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

Based on the value of Tc we have,

- High temperature superconductors
- Low temperature superconductors

Type I (or) Soft superconductors

When the Super conductor is kept in the Magnetic field and if the field is increased the super conductor becomes a normal conductor immediately at critical magnetic field as shown in fig. This type of materials are termed as Type 1 super conductor.

Characteristics

1. They exhibit complete Meissner Effect.
2. They have only one critical magnetic field value.
3. Below the critical magnetic field (H_c) the material behaves as superconductor and above H_c the material behaves as normal conductor. These are called as Soft superconductors

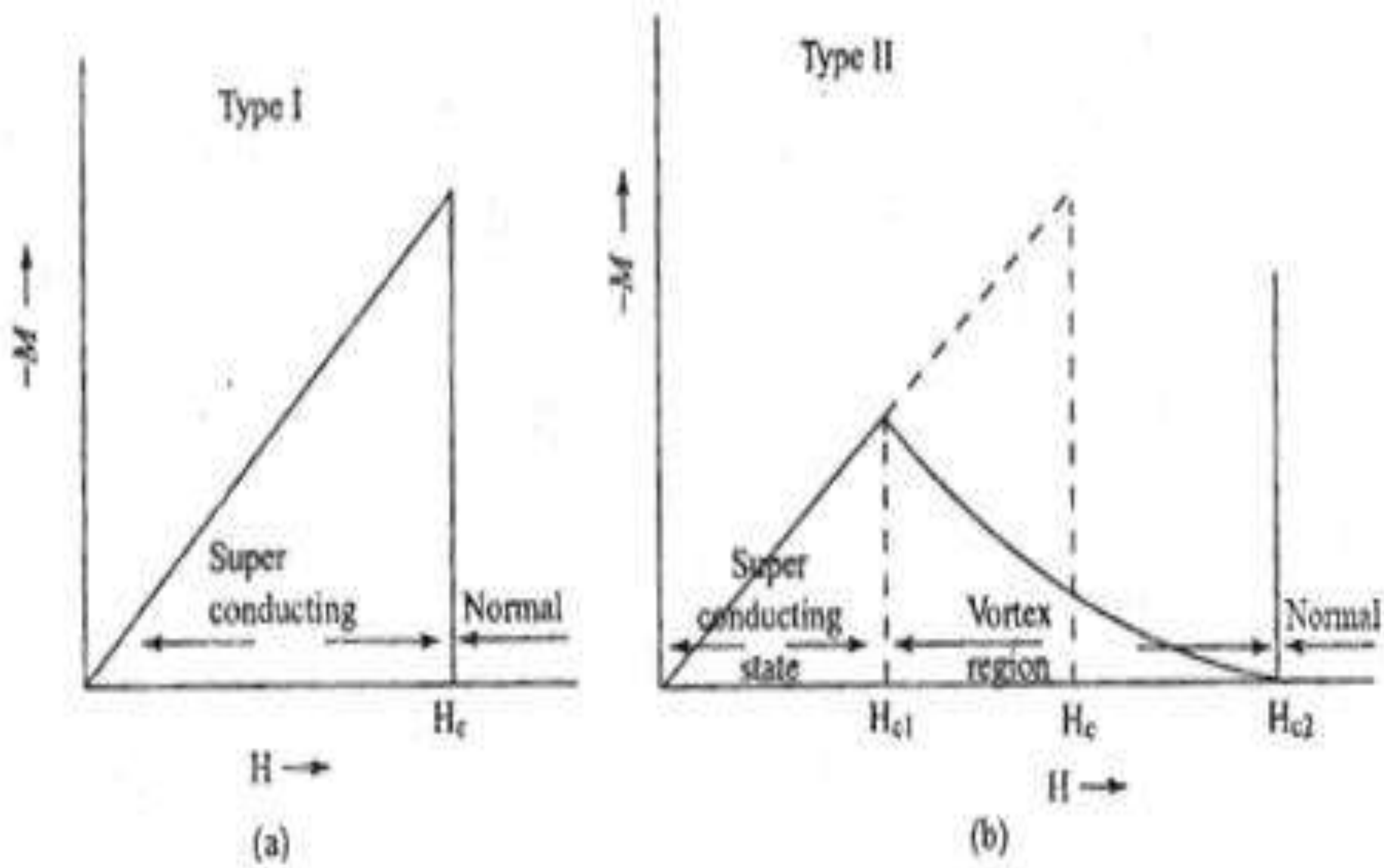
Type II (or) Hard superconductors

In type II superconductor, the magnetic field is excluded from the material and the material loses its superconducting property gradually rather than abruptly

Characteristics

1. They do not exhibit a complete Meissner Effect.
2. They have two critical magnetic field values. Lower critical magnetic filed [H_{C1}] and Higher critical magnetic field [H_{C2}].
3. Below H_{C1} the material behaves as superconductor and above the material behaves as normal conductor. The region in between [H_{C1}] and [H_{C2}] is called mixed state or vortex region. These are called as Hard superconductors

Type I & Type II Superconductors



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BCS THEORY

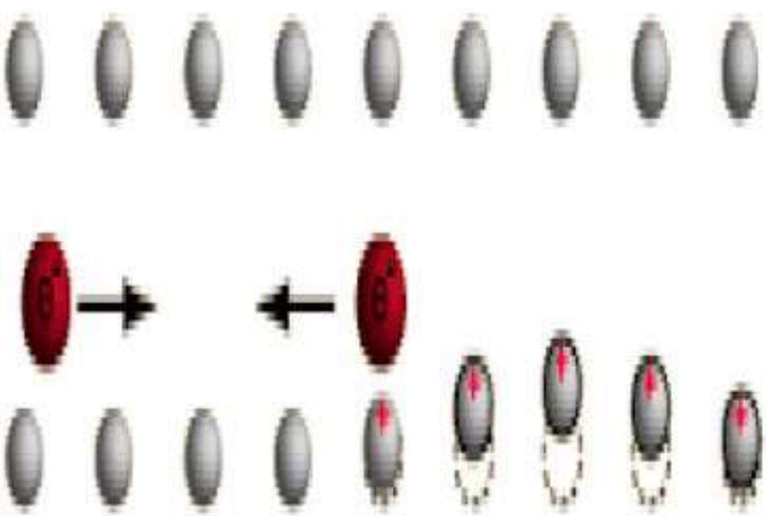
BCS THEORY (Bardeen, Cooper and Schrieffer) BCS theory is the first microscopic theory of superconductivity since its discovery in 1911. It explains,

The interaction of phonons and electrons.

John Bardeen, Leon Cooper and Robert Schrieffer received the Nobel prize in 1972 for the development of the theory of Superconductivity.

Cooper pairs : A key conceptual element in this theory is the pairing of electrons close to the Fermi level into Cooper pairs through interaction with the crystal lattice.

Phonon:



Lattice of super conducting material

A phonon is a quantum mechanical description of an elementary vibration motion in which a lattice of atoms or molecules uniformly oscillates at a single frequency.

When an electron is advancing through a path in between two sets of ions in the lattice.

Electron attracts the nearby +ve charges and the lattice get distorted.

This distortion produce some density variation in the crystal.

It will propagate like a wave

Cooper pairs:

- Cooper pair is a pair of electrons (or fermions) bound together at low temperatures in a certain manner first described in 1956 by American physicist Leon Cooper.

- An electron in a metal normally behaves as a free particle. The electron is repelled from other electrons due to their negative charge, but it also attracts the positive ions that make up the rigid lattice of the metal.

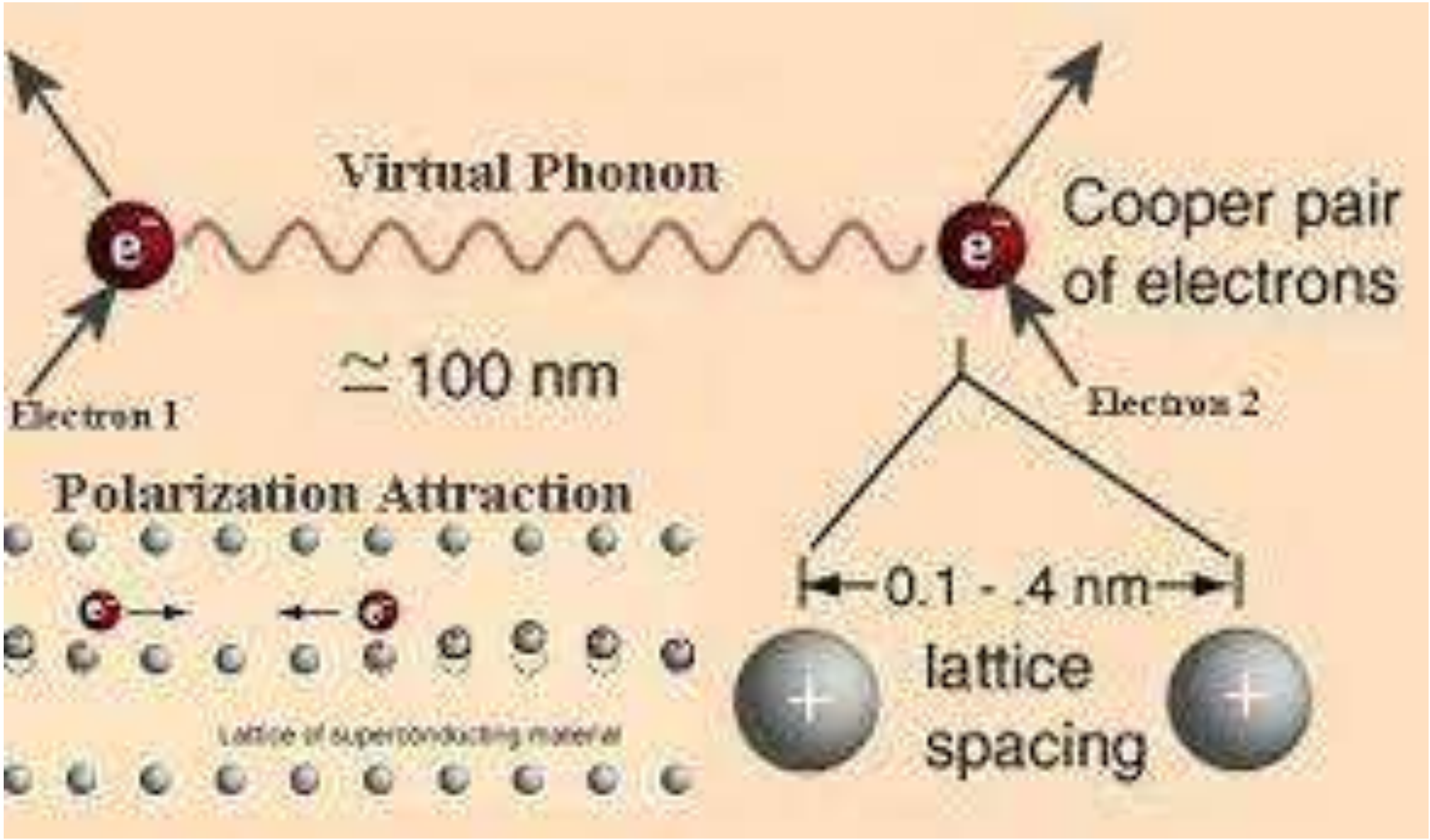
- This attraction distorts the ion lattice, moving the ions slightly toward the electron, increasing the positive charge density of the lattice in the vicinity.

- This positive charge can attract other electrons. At long distances, this attraction between electrons due to the displaced ions can overcome the electrons' repulsion due to their negative charge, and cause them to pair up.

- The rigorous quantum mechanical explanation shows that the effect is due to electron–phonon interactions.

BCS THEORY

Cooper pairs:



APPLICATIONS OF SUPERCONDUCTORS

General Applications

1. Electric generators can be made by using superconductors with smaller size, less weight and low energy consumption.
2. Superconductors can be used for the transmission of power over very long distances.
3. Superconductors can be used in switching Devices.
4. The superconductors can be used in sensitive electrical instruments.
5. It can be used as a memory or storage element in computers.
6. These are used to design Cryotron, Maglev, Josephson Devices and SQUID.
7. DC superconducting motors are used in ship propulsion and in large mills.
8. Superconducting magnetic field may be used to launch satellite into orbit directly from the earth without use of rockets.
9. Ore separation can be done by using machines made of superconducting magnets.
10. These are used in NMR (Nuclear Magnetic Resonance) imaging equipments which is used for scanning purposes.
11. Superconductors are used for the detection of brain tumor, defective cells, etc.,
12. Superconducting solenoids are used in magneto hydrodynamic power generation to maintain the plasma in the body.

Applications of superconductors:

Medical :

Magnetic resonance imaging & Biotechnical engineering

Electronics:

SQUIDs

Transistors

Josephson Junction devices

Circuitry connections

Particle accelerators & Sensors

Industrial :

Magnets sensors, Transducers magnetic shielding & Power Generation Motors Transmission

Transportation Magnetically levitated vehicles & Marine propulsion


Thank you!

Superconducting QUantum Interference Device (SQUID) :

- A superconducting quantum interference device (SQUID) is a mechanism used to measure extremely weak signals.
- Super current changes periodically with magnetic flux. Junction region have much lower value than the rest of the superconducting ring.
- When the current in the junction exceeds the critical value, the junction become normal, then the fluxons penetrate through the link.
- So the current falls to critical value and then the link reverts to superconducting state.
- Then the junction act as a gate.