Electric Properties Continued….

❖ Concept of Superconductivity

➢ Superconductivity

The superconductivity phenomenon was discovered in 1911 by the great Dutch physicist Heike Kamerlingh Onnes in his laboratory at the Leiden University. He was awarded the noble prize in 1913. Thus, we can define superconductivity as a phenomenon of absolutely zero electrical resistance and expulsion of magnetic fields occurring in certain materials when cooled below a characteristic critical temperature (T_c). The materials which exhibit the property of superconductivity are known as superconductors.

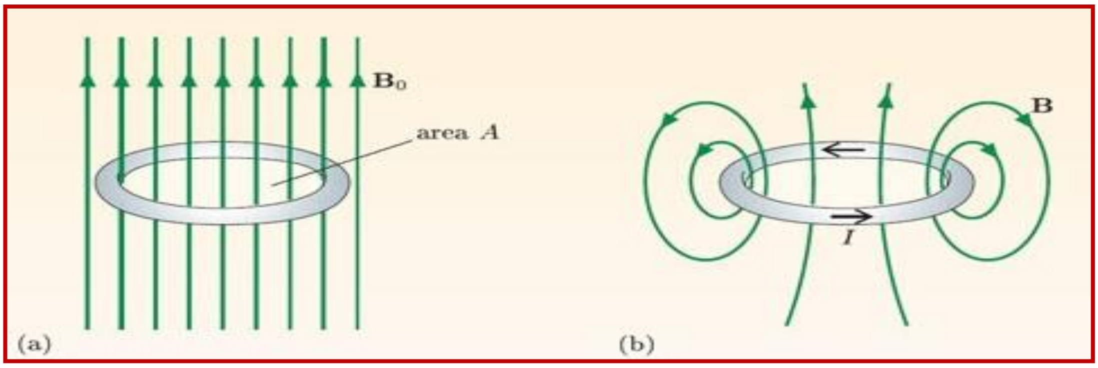


Figure 1: (a) A superconductor in magnetic field (b) Persistent current flowing in superconductor after the removal of field.

➢ Hallmarks of superconductivity

A material has to exhibit two important characteristic properties in order to become a perfect superconductor. These two characteristics / hallmarks are discussed below.

(i) Zero resistivity

Electrical resistance is a measure of the degree to which an object opposes an electric current through it, measured in ohms. Its reciprocal quantity is electrical conductance measured in Siemens. Assuming a uniform current density, an object's electrical resistance is a function of both its physical geometry and the resistivity of the material it is made from:

$$\mathbf{R = \rho . l / A}$$

Where, $\mathbf{l} \Rightarrow$ represents the length

$\mathbf{A} \Rightarrow$ represents the cross sectional area, and

$\rho \Rightarrow$ represents the resistivity of the material

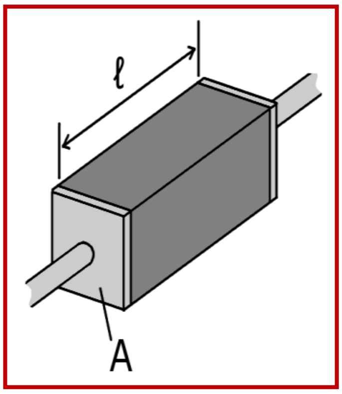


Figure 2: A piece of resistive material with electrical contacts on both ends.

Temperature dependence

Near room temperature, the electric resistance of a typical metal varies linearly with the temperature. At lower temperatures (less than the Debye temperature), the resistance decreases as T^5 due to the electrons scattering off of phonons. At even lower temperatures, the dominant scattering mechanism for electrons is other electrons, and the resistance decreases as T^2. At some point, the impurities in the metal will dominate the behaviour of the electrical resistance which causes it to saturate to a constant value. The value of the residual resistivity of a metal is decided by its impurity concentration. So, more impure the metal, the larger will be its residual resistivity as shown in figure 3. The diagram below shows the variation of resistance of metals with temperature where, T_c represents the temperature at which a superconductor loses resistance, also known as the critical or transition temperature.

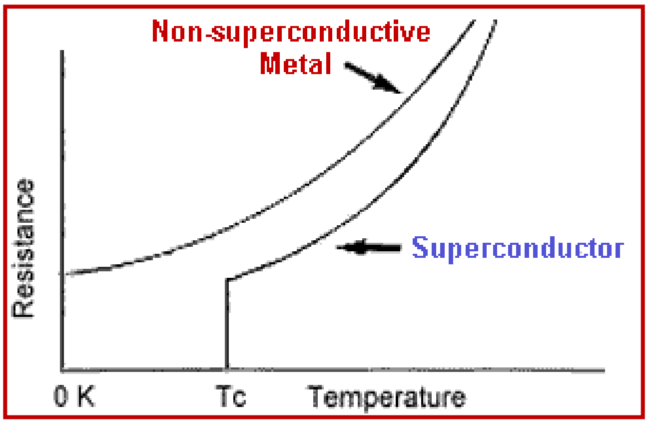
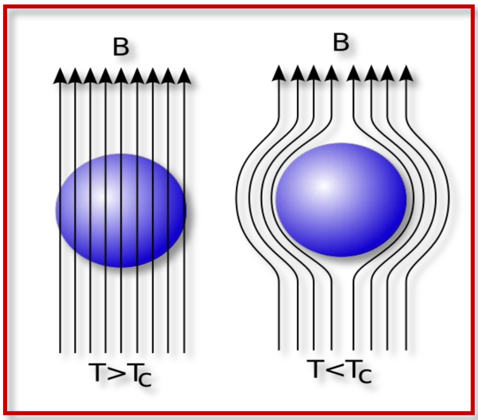
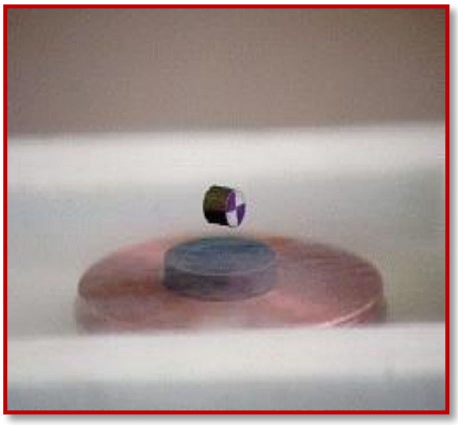


Figure 3: Variation of resistance of metals with temperature

(ii) Perfect diamagnetism (Meissner effect)

In 1933, the Meissner effect was discovered by two German physicists known as Walther Meissner and Robert Ochsenfeld while measuring the magnetic field distribution outside the superconducting tin and lead samples. When a magnetic field was applied, the samples cooled below its Tc and the interior magnetic fields were cancelled. Thus, it was concluded that B = 0 inside the superconductor i.e. there is an expulsion of magnetic field. This phenomenon came to be known as Meissner Effect and is the second hallmark of superconductivity.





(a) **(b)**

Figure 4: (a) Meissner effect with magnetic field lines (represented as arrows) excluded from a superconductor when cooled below its critical temperature. (b) A magnet levitating above a superconductor cooled by liquid nitrogen.

In superconducting state the magnetic flux density inside the superconductor i.e B = 0.

Therefore, we can write: $\mathbf{B = 0}$

$$\Rightarrow \boldsymbol{\mu(M + H) = 0} \qquad [B = \mu(M + H)]$$

$$\Rightarrow \mathbf{M = - H} \qquad \text{(For superconductor)}$$

Therefore, the susceptibility is given by:

$$\boxed{\chi = \frac{M}{H} = \mathbf{-1}} \qquad \text{(Perfect Diamagnet)}$$

Where, $\mathbf{B} \rightarrow$ Magnetic flux density

$\boldsymbol{\mu} \rightarrow$ Permeability of the material

$\mathbf{M} \rightarrow$ Intensity of magnetization

$\mathbf{H} \rightarrow$ Applied magnetic field

$\chi \rightarrow$ Magnetic susceptibility of the material

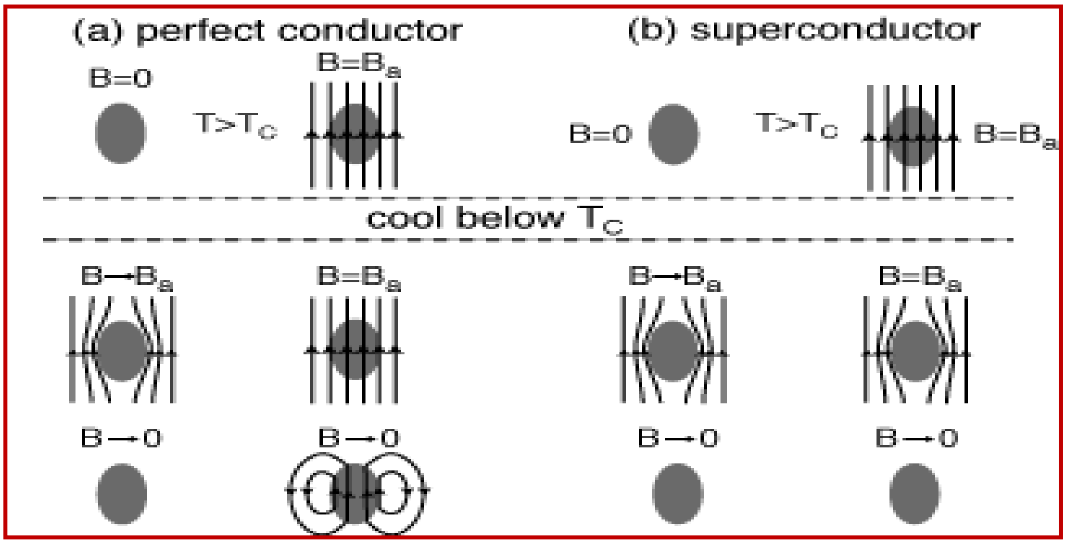


Figure 5 (a): Behaviour of a 'perfect conductor', i.e. a material which merely has zero resistivity below T_c (b): situation for a genuine superconductor which displays the Meissner effect.

Therefore, we can say that superconductors are not only perfect conductors but perfect diamagnetic materials too.

- **Critical parameters of superconductivity**

There three most important critical parameters of superconductivity are described below.

(i) Critical / Transition Temperature (T_c)

It refers to the temperature at which change of state occurs from superconducting to normal state or vice versa. Below is a list of elements showing their respective Critical / Transition Temperature (T_c).

Table1: Different elements with their corresponding critical temperature (T_c) value.

Element	T_c
Lead (Pb)	7.20K
Lanthanum (La)	4.88K
Tantalum (Ta)	4.47K
Mercury (Hg)	4.15K
Tin (Sn)	3.72K
Nb_3Ge	23K
Nb_3Si	19K
Nb_3Sn	18K

(ii) Critical field (H_c)

The minimum magnetic field required at a given temperature to destroy superconductivity is known as critical field. It is given by the relation as:

$$H_c = H_o [1- (T/T_c)^2]$$

Where, $H_c \rightarrow$ Critical field required at temperature T

$H_o \rightarrow$ Critical field required at 0K

$T_c \rightarrow$ Critical temperature (when $H_c = 0$)

Transition temperature can be reduced with increment in the critical field.

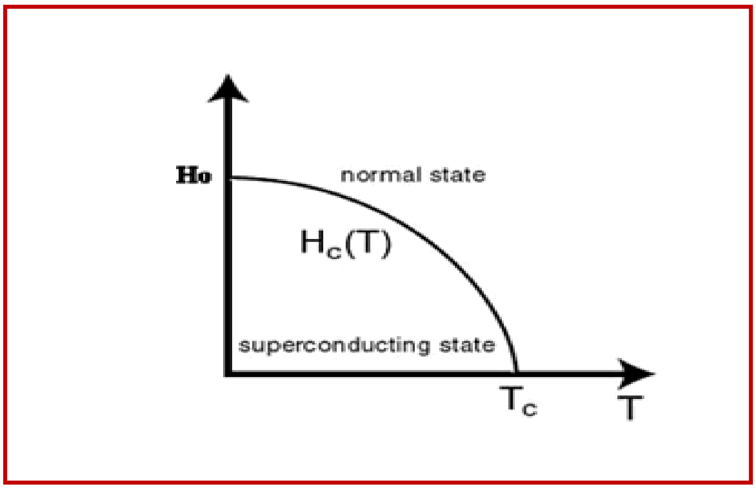


Figure 6: Effect of magnetic field and temperature on a superconductor.

(iii) Critical current density (J_c)

The minimum current density required at a given temperature to destroy superconductivity is known as critical current density (J_c).

All the three critical parameters i.e. T_c, H_c, J_c depends on each other and forms a surface as shown in the figure 7. Thus, it can be stated that the material remains in the superconducting state when all the critical parameters stay on this surface.

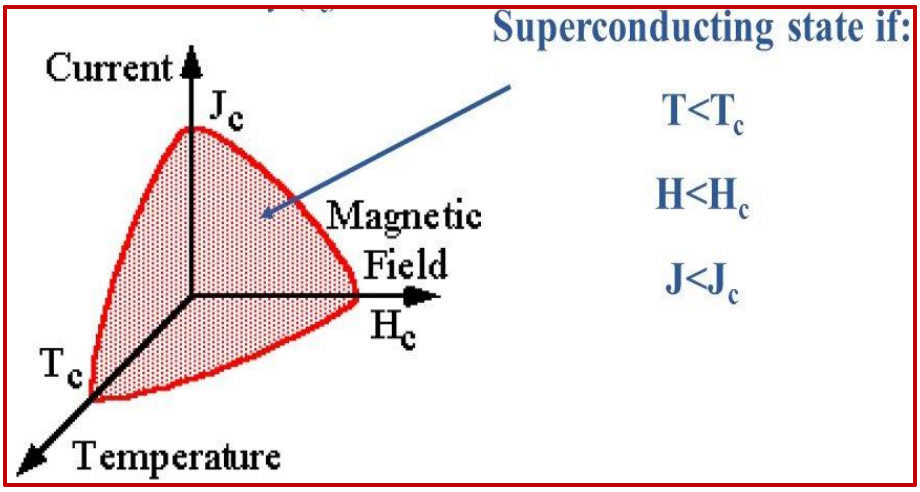


Figure 7: Schematic of the regions of current density, magnetic field and temperature within which a material remains superconducting

- **Silsbee Rule:** If a superconducting material carries a current such that magnetic field which it produces is equal to the critical field then superconductivity will disappear.
- **Types of superconductors**

Superconductors can be categorized into different types based on different factors. The categorization is discussed as below:

(i) Based on magnetic properties

In this category the superconductors are categorized into two types namely Type I and Type II. This classification is done on the basis of the response of the material in an external magnetic field. The classification is given below as:

- **Type I superconductors**

These superconductors exhibit an abrupt / very sharp transition between the changes of state from normal to superconducting or vice versa. They are also known as ideal or soft superconductor and totally exclude an applied magnetic flux. The values of Critical field (H_c) and the Critical temperature (T_c) are low so they have practical no practical application for superconducting magnets. These superconductors completely follow the Silsbee Rule and Meissner effect. Some examples are Pb, Al, Hg, etc. The figure 8 below clearly shows that no mixed state is present in type I superconductor. It also shows that when an external magnetic field is applied to a Type I superconductor the induced magnetic field exactly cancels that applied field until there is an abrupt change from the superconducting state to the normal state.

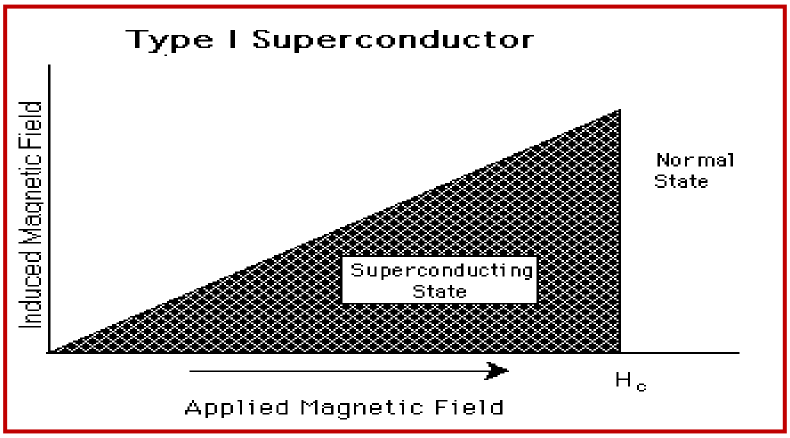


Figure 8: Induced magnetic field versus applied magnetic field of a Type I superconductor.

- **Type II superconductors**

These superconductors exhibit a gradual transition across a region of mixed state behaviour. They are also known as non ideal or hard superconductor and totally exclude magnetic flux when the applied magnetic field is low, but only partially exclude it when the applied field is higher. The values of Critical field (H_c) and Critical temperature (T_c) are high. These superconductors incompletely follow the Silsbee rule and Meissner effect (in intermediate region). Some of the examples of this type are YBCO, Nb_3Sn, NbTi, etc. Figure 9 below shows a Type II superconductor having two critical fields, H_{c1} and H_{c2}. Under the lower critical field (H_{c1}) the superconductor excludes all the magnetic field lines and behaves as a perfect superconductor. But the field begins to penetrate into the material in the form of flux vortices when the field strengths are between H_{c1} and H_{c2} .The pipe – like vortices are swirling tubes of electrical current induced by the magnetic field into the superconductor. Thus, the material is said to be in the mixed state, with some of the material in the normal state and part still superconducting. As the applied magnetic field increases the number of vortices inside the material also increases. Ultimately, when $H \geq H_{c2}$ the materials changes to normal state as there are too many vortices to sustain superconductivity.

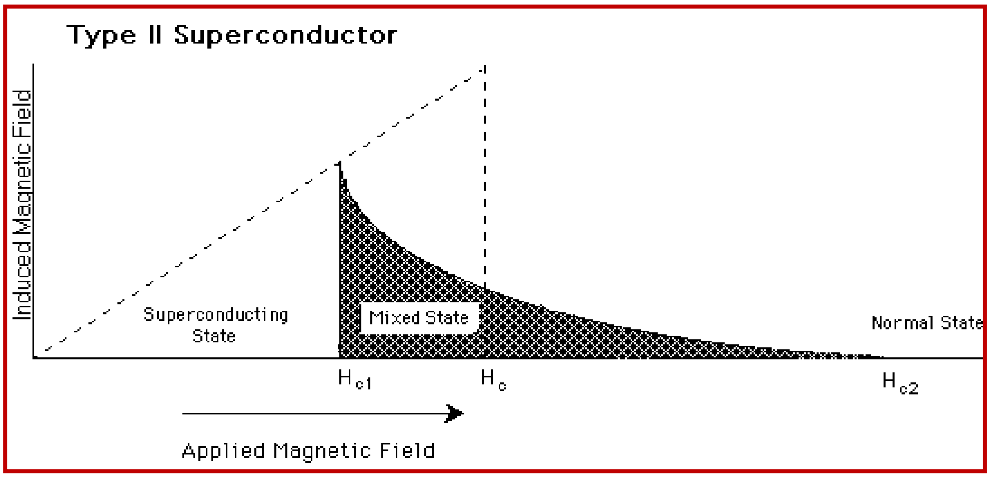


Figure 9: Induced magnetic field versus applied magnetic field of a Type II superconductor.

When a type II superconductor with flux vortices inside is subject to current, the vortices are moved by a magnetic force known as Lorentz force. The equation is given as: Lorentz Force: $F_L = | J \times B |$

Where, F_L is the macroscopic Lorentz force in a superconductor.

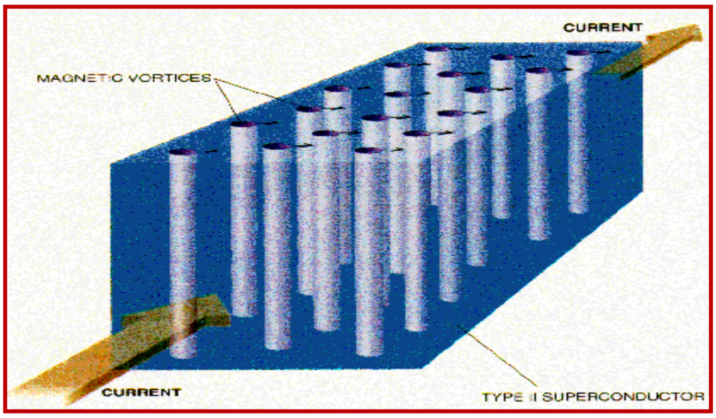


Figure 10: A current-carrying type II superconductor in the mixed state showing magnetic vortices

Figure 10 above clearly shows that the Lorentz force pushes the magnetic vortices at right angles to the current flow. This type of motion of vortices results into energy dissipation, i.e an electric field (voltage) develops, and is therefore undesirable. However, the Lorentz force can be countered by pinning the vortices. All kinds of impurities and defects in the superconductors act as pinning centres, where the vortices can lower their energy. The vortices are attached to these pinning sites and a lossless current flow is thus enabled. The pinning force is given by:

$$\boxed{F_p = B\, J_c}$$

The ability of a superconductor to undergo superconductivity at high magnetic fields is determined by the values of the upper critical field (H_{c2}). So, it is necessary to have a high H_{c2} value from application point of view. However, Type II superconductors have much larger values of H_{c2} and find application in different fields like MRI (Magnetic Resonance Imaging), etc.

(ii) Based on the understanding we have about them

Under this category the superconductors are classified into two different types:

- **Conventional superconductors:** These are the materials that display superconductivity property which can be fully explained by the help of BCS theory or related theories which are derived from the BCS theory. They can be either Type I or Type II superconductors. Most elemental superconductors are conventional.
- **Unconventional superconductors:** These are the materials that display superconductivity which can't be explained by either the conventional BCS theory or the related theories which are derived from the BCS theory. Until now, there has been no satisfactory theory which could fully explain the unconventional superconductors.

(iii) Based on critical temperature

Superconductors can be categorized into two types based on the critical field namely Low Temperature Superconductors (LTS) and High Temperature Superconductors (HTS).

- **Low-temperature superconductors (LTS):** These are the superconductors whose critical temperature is below the boiling point of liquid nitrogen (77K). They require more aggressive cooling technique to reach its critical temperature (T_c).Example: Nb_3Sn
- **High-temperature superconductors (HTS):** These are the superconductors whose critical temperature is above the boiling point of liquid nitrogen (77K). Example: YBCO, BSCCO.

- **Factors affecting superconductivity and transition temperature (T_c) of material**

(i) Temperature: Superconductivity decreases with increase in temperature.

(ii) Frequency: Superconductivity decreases with increase in frequency. Resistivity of superconductor increases with frequency up to 10MHz and above this frequency it becomes same as normal state.

(iii) Mechanical stress / pressure: Transition temperature of superconducting material can be varied with application of mechanical stress.

(iv)Isotropic mass (M):

$$T_c = \frac{\text{constant}}{\sqrt{M}}$$

For example: Mercury (Hg) has 2 isotopes.

Hg	M	T_c
I	199.6	4.185°K
II	203.4	4.16°K

Thus, for Hg, $T_c \approx 4.1$°K

- **Applications of superconductivity**

The phenomenon of superconductivity has many important practical implications. Superconducting magnets capable of generating high fields with low power consumption are currently being employed in scientific test and research equipment. In addition, they are also used for magnetic resonance imaging (MRI) in the medical field as a diagnostic tool. Abnormalities in body tissues and organs can be detected on the basis of the production of cross-sectional images. Chemical analysis of body tissues is also possible using magnetic resonance spectroscopy (MRS). Numerous other potential applications of superconducting materials also exist. Some of the areas being explored include:

(1) Electrical power transmission through superconducting materials - power losses would operate at low voltage levels

(2) Magnets for high-energy particle accelerators

(3) Higher-speed switching and signal transmission for computers and

(4)High speed magnetically levitated trains, wherein the levitation results from magnetic field repulsion.