Module 2

Electrical properties of materials and application

Electrical Properties of Solids:
Conductors: Quantum Free Electron Theory of Metals: Assumptions, Fermi-energy, Fermi factor, Variation of Fermi Factor with Temperature and Energy, Mention of expression for electrical conductivity.
Dielectric Properties: Polar and non-polar dielectrics, Electrical Polarization Mechanisms, internal fields in solids, Clausius-Mossotti equation (Derivation), Solid, Liquid and Gaseous dielectrics.Application of dielectrics in transformers, Capacitors, Electrical Insulation. Numerical Problems.
Superconductivity: Introduction to Superconductors, Temperature dependence of resistivity, Meissner Effect, Critical Field, Temperature dependence of Critical field, Types of Super Conductors, BCS theory (Qualitative), High Temperature superconductivity, SQUID, MAGLEV, Numerical problems.

Electrical Properties of Solids

2.1.1 Assumptions of Quantum free electron theory of metals:

It was proposed by Sommerfeld with the following important assumptions.

1. Energy values of conduction electrons are quantized and are realized in terms of set of energy levels.
2. Distribution of electrons in various allowed energy levels takes place according to Pauli's exclusion principle.
3. The electron travels in a constant potential inside the metal but stay confined within its boundary.
4. The attraction between electron and ions and the repulsion between electrons are ignored.

These assumptions introduced the concept of Fermi energy and Fermi level.
If there is 'n' number of electrons present in an atom, then there exists 'n' number of energy levels.

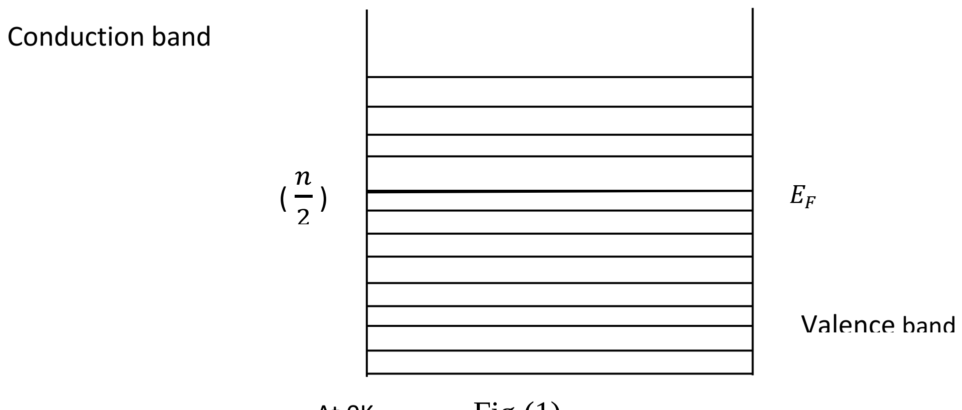


Fig (1)

Obeying Pauli's principle, any two electrons with different quantum numbers occupy any of these energy levels starting from lowest energy level. Thus among 'n' level ($\frac{n}{2}$) levels gets filled, and this ($\frac{n}{2}$) level is the highest possible energy level for an electron in an atom. It is referred as Fermi level and corresponding energy is called Fermi energy.
All the energy levels below Fermi level are completely filled and above are completely empty. The Fermi level may be partially or completely filled.

2.1.2 Fermi energy

Fermi-Dirac statistics

Statistical physics can be applied to a collection of particle in an effort to relate microscopic properties to macroscopic properties. In the case of electrons it is necessary to use quantum statistics, with the requirement that each state of the system can be occupied by only one electron. Each state is specified by a set of quantum numbers. The electrons are found to be distributed in various energy states in a proper way. This is because they acquire energy obeying a statistical rule.

Fermi–Dirac statistics can be applied to the assembly of particles which obey Pauli's exclusion principle. The particles must be identical, indistinguishable and have spin ½. As electrons satisfy the above conditions they obey Fermi-Dirac statistics. Fermi-Dirac statistics permits the evaluation of probability of finding electrons occupying energy levels in a certain range. The probability that a particular state having specific energy is occupied by one of the electrons in a solid is given by

$$f(E) = \frac{1}{e^{(E-E_f)/kT} + 1}$$

Where f(E) is called Fermi-Dirac distribution function or Fermi factor and E_F is called **the Fermi energy**

2.1.3 Fermi factor

Fermi factor is the probability of occupation of a given energy state for a material in thermal equilibrium. The probability f(E) that a given energy state with energy E is occupied at a steady temperature T is given by,

$$f(E) = \frac{1}{e^{(E-E_f)/kT} + 1}$$

2.1.4 Variation of fermi factor with temperature and energy

Dependence of Fermi factor f (E) on temperature and Effect on occupancy of Energy levels

Case (i) : probability of occupation for $E< \boldsymbol{E_F}$ at T = 0.

When T = 0 and $E< \boldsymbol{E_F}$, we have for the probability,

$$f(E) = \frac{1}{e^{(E-E_f)/kT} + 1}$$

$$f(E) = \frac{1}{e^{-\infty}+1} == 1/0+1$$

$$f(E) = 1$$

$$f(E) = 1 \text{ , for } E< \boldsymbol{E_F}$$

Here f(E) = 1 means the energy level is certainly occupied and $E< E_F$ applies to all the energylevels below E_F.Therefore at T = 0, all the energy levels below the Fermi level are occupied

Case (ii): probability of occupation for $E > E_F$ at T = 0.

When T = 0 and $E> \boldsymbol{E_F}$, we have for the probability,

$$f(E) = \frac{1}{e^{(E-E_f)/kT} + 1}$$

$$f(E) = \frac{1}{e^{\infty}+1} = \frac{1}{\infty}$$

$$f(E) = 0$$

$$f(E) = 0 \text{ , for } E > \boldsymbol{E_F}$$

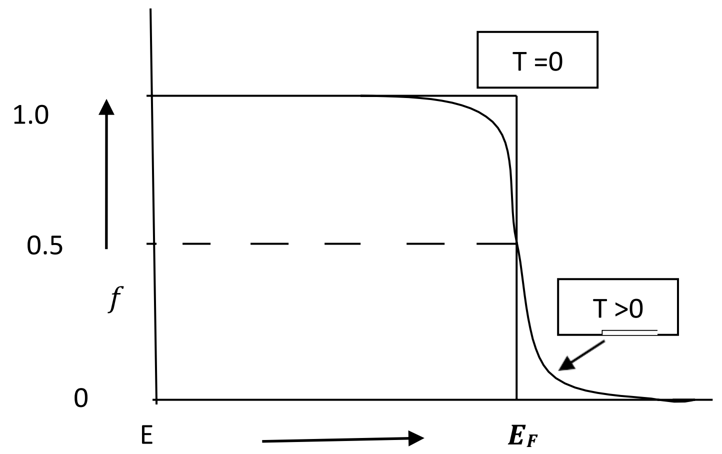
Therefore at T = 0, all the energy levels above Fermi level are unoccupied. Of f(E) for different energy values, becomes a step function in the above Fig (2)

Case (iii): probability of occupation at ordinary temperature

At ordinary temperature, though the value of probability remains 1 for E<< E_F it starts decreasing from 1 as the values of E become closer to E_F, thus the value of f(E) becomes ½ atE =E_F, this is because E =E_F

$$e^{E-Ef/KT} = e^0$$

$$f(E) = \frac{1}{e^{E-Ef/KT} + 1} = 1/1+1 = ½$$



Dielectric Properties

2.2.1 Polar and non-polar dielectrics

Dielectrics are the insulators which can transmit the electrical effects without conducting. Or Dielectrics are the materials which have the ability to get electrically polarized and in which electric field can exist.

There are two types of dielectric materials

1. Polar dielectrics
2. Non-Polar dielectrics

Electric Dipole: Two equal and opposite charges separated by a small distance is called as electric dipole.

Dipole Moment: The product of magnitude of one of the charges and the distance of separation between the two charges is called as dipole moment.

If +q and –q are the two charges separated by a distance d, then dipole moment

$$\mu = \text{charge x distance of separation}$$

$$\mu = qd$$

The unit of μ is Coulomb-meter in SI system. It is a vector quantity.

Polarization: The process of reorientation of dipoles in a dielectric in the presence of an external field is called as electric polarization. It can be defined as the dipole moment per unit volume.

If μ be the dipole moment and V the volume of the dielectric, then polarization P is given by

$$P = \frac{\mu}{V}$$

Polar Dielectrics:

The dielectrics having permanent electric dipole and the center of positive and negative charges not coinciding are called as polar dielectrics. Eg: - water, HCl, NaCl etc.

Non-Polar Dielectrics:

The dielectrics having no permanent electric dipoles and the centers of positive and negative charges do coincide resulting in zero dipole moment are called as non-polar dielectrics. Eg: - H, N etc.

Dielectric Constant ($\boldsymbol{\varepsilon_r}$)

It is a physical quantity which depends on the structure of the atoms inside the material. It is defined as the ratio of absolute permittivity of the given material to the absolute permittivity of air or vacuum. If $\boldsymbol{\varepsilon 0}$ is the absolute permittivity of air and ε is that of the dielectric material then relative permittivity $\boldsymbol{\varepsilon r}$ is

$$\boldsymbol{\varepsilon_r} = \frac{\epsilon}{\varepsilon_0}$$

OR

The ratio of capacitance of capacitor in material medium to the capacitance in air medium can be defined as dielectric constant.

$$\varepsilon_r = \frac{C_m}{C_a}$$

2.2.2 Polarization

The induced dipole moment per unit volume of the dielectric is called as polarization

That is

$$Polarization = \frac{\text{Dipole moment}}{\text{Volume of dielevtric material}}$$

$$P = \frac{\mu}{V} \quad \text{--------------} \ (1)$$

The unit of P is C/m^2.

The polarization is proportional to the external field E

$$P \ \alpha \ E$$

$$P = \varepsilon_0 \, (\varepsilon_r - 1)E$$

Polarizability ($\boldsymbol{\alpha}$)

When the dielectric material is subjected to an external electric field the dipole moment is directly proportional to the field. Let μ be the electric dipole moment acquired by an atom and E be the electric field. Then $\mu \ \alpha \ E$

Therefore $$\mu = \alpha E$$

$$\alpha = \frac{\mu}{E}$$

α is called as Polarizability.

Thus, Polarizability can be defined as the ratio of dipole moment acquired by an atom to applied external electric field. SI unit: Fm^2.

2.2.3 Electrical Polarization Mechanisms

There are four types of electric polarization.

1. Electronic polarization
2. Ionic polarization
3. Orientation polarization
4. Space charge polarization

- Electronic polarization

  This kind of polarization observed in non-polar dielectrics. When an external electric field is applied to dielectrics, positive and negative charges are displaced. The separation created between the charges leads to development of a dipole moment. This process occurs throughout the materials. The electronic Polarizability is given by,

$$\alpha = \frac{\varepsilon_0(\varepsilon_r - 1)}{N}$$

  Where N = number atoms per unit volume.

- Ionic polarization

  It is observed in dielectric materials which possess ionic bonds. Eg: - NaCl When ionic solids are subjected to an external field, the adjacent ions of opposite sign undergo displacement. The displacement causes an increase or decrease in the distance of separation between the atoms depending upon the location of the ionic pairs in the lattice.

- Orientation polarization (Molecular Polarization)

  It is observed in polar molecules. It is due to reorientation of the molecular dipoles present in a polar dielectric material in opposite direction to that of the applied field.

  The orientation polarization is given by,

$$\alpha_0 = \frac{\mu^2}{3KT}$$

  Where, μ = dipole moment, K = Boltzmann's constant, and T = absolute temperature.

- Space Charge polarization

  It is observed in multiphase dielectrics in which there is a change in resistivity between different phases. When an electric field is applied, the charges accumulate at the interface, at very high temperature resulting in nonzero dipole moment in the low resistive region.

2.2.4 Internal fields in solids

When a dielectric material is subjected to an external field, each atom develops a dipole moment and acts as dipole. Due to electric dipoles present in dielectrics, an electric field is developed inside it. Thus, the resultant field is the sum of external field and electric field due to electric dipoles. This resultant field is called the internal field. 'Internal field is the electric field that acts at the site of any given atom in a solid or liquid placed in an external field'.

It is given by $E_i = E + E^1$

Where E = applied field, E^1 = induced field.

In case of gases, the dipole interaction is nil because the density of gas is less. Therefore Ei = E (for gases).

2.2.5 Expression for the Internal Field for One Dimensional Array of Dielectric Solid

The expression for internal field for one dimensional dielectric solid is given by,

$$\boxed{E_i = E + \frac{1.2\alpha_e E_i}{\pi\varepsilon_0 d^3}}$$

Where, E_i – Internal field

α_e -Electronic Polarizability

E- Applied field

μ- induced dipole moment

d- Inter-atomic distance

2.2.6 Expression for internal field for three dimensional cases and Lorentz field

Expression for Lorentz field is given by,

$$E_i = E + \frac{P}{3\varepsilon_0}$$

Where, E – Applied electric field
P- Polarization

2.2.7 Clausius-Mossotti equation (Derivation)

This equation gives the relation between dielectric constant (macroscopic quantity) and electronic Polarizability (microscopic quantity)

Polarization is given by $P = \epsilon_0 E_o (\epsilon_r - 1)$

E_o is the applied electric field.

Therefore $$E_o = \frac{P}{\epsilon_0(\epsilon_r - 1)} \quad \text{.............. (1)}$$

The dipole moment is proportional to internal field.

i.e., $\mu \; \alpha \; E_i$

Therefore, $$\mu = \alpha E_i \quad \text{.............. (2)}$$

Where, α = Polarizability

When there are N atoms per unit volume, then

$$P = \mu N$$

Using equation 2, we get,

$$P = N \alpha E_i$$

$$E_i = \frac{P}{N \alpha} \quad \text{.............. (3)}$$

The internal field inside the dielectric is given by,

$$E_i = E_0 + \frac{P}{3 \varepsilon_0}$$

Therefore, $$\frac{P}{N\alpha} = \frac{P}{\epsilon_0(\epsilon_r - 1)} + \frac{P}{3\varepsilon_0}$$

$$\frac{1}{N\alpha} = \frac{1}{\epsilon_0(\epsilon_r - 1)} + \frac{1}{3\varepsilon_0}$$

$$\frac{1}{N\alpha} = \frac{2 + \epsilon_r}{3\,\varepsilon_{0(\epsilon_r - 1)}}$$

Rearranging, $$\boldsymbol{\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{N\alpha}{3\varepsilon_0}}$$

This is known as C-M Equation.

Importance of C-M equation is it gives the relation between microscopic and macroscopic quantity.

2.2.8 Solid, Liquid and Gaseous dielectric materials: Solid dielectric materials.

Solid dielectric materials:

- **Mica**: It is an inorganic mineral material, made of the silicate of aluminum with silicate of soda, potash and magnesia. It is crystalline in nature and can be divided into very thin flat sheets. It has high dielectric strength and low dielectric loss. It is used in electric irons, hot plates and toasters for insulation. Its dielectric constant varies from 5 to 7.5 and dielectric strength between 700 kV/mm and 100kV/mm.
- **Glass:** It is an inorganic material made by different oxides like SiO2, ZnO and MgO. It is brittle and hard with good mechanical strength and low dielectric loss. Used in capacitors, TV tubes, electric lamps and laminated boards. Its dielectric constant varies from 3.7 to 10 and dielectric strength between 3 kV/mm and 5 kV/mm.

- **Rubber:** It is an organic polymer, may be natural or synthetic. It has a good electrical and thermal properties and high tensile strength. It is used in construction of storage battery housings, insulation for electric wires, tapes, transformers, etc. Its dielectric constant varies from 0.01 to 0.03
- **Asbestos:** It is a naturally occurring mineral of fibrous nature consisting of magnesium silicate. It has high dielectric loss and low dielectric strength and can withstand very high temperature. It is used to prevent current flow in the outer body of electrical appliances like electrical iron box, oven, etc. It is widely used in the form of paper tape, cloth and board.
- **Ceramics:** It is generally non-metallic compounds such as silicates, aluminates, oxides, carbides, nitrides and hydroxides. They are hard, strong, and dense. They have excellent dielectric and mechanical properties. They are not affected by moisture and by chemical agents except with strong acid and alkalis. They are widely used in insulators for switches, plug holders, cathode heaters, etc. Its dielectric constant varies from 4 to 10.

<u>Liquid dielectric materials</u>

- **Mineral insulating oils:** Transforms oil, capacitor oil and cable oil, used as coolant in transformers and capacitors. They are directly obtained from crude petroleum by distillation. They are used as coolant in transformers and capacitors.
- **Synthetic insulating oils:** Used for the purpose of cooling in high-tension transformers. They are very cheap. E.g. askarels, sovol.
- **Miscellaneous insulating oils:** Silicon liquid and vegetable oil used in high tension transformers. Silicone liquid is costly compared to synthetic insulating oils.

<u>Gaseous dielectric materials</u>

- **Air:** Used in long distance electrical transformers and air –capacitors. Compressed air-as arc extinguishing medium in air-blast circuits breakers. It’s used as dielectric in long-distance electrical transmissions and in air capacitor.
- **Nitrogen:** Chemically inert, used as a dielectric medium to prevent oxidation, used in gas filled high-voltage cables as an inert medium to replace air in the space above the oil.
- **Hydrogen:** Dielectric strength of H2 is about 65% higher than air, used as a cooling medium in large turbo –generators and synchronous motors. The injurious effect of hydrogen gas is considered to be negligibly small, since during the discharge it does not produce ozone or oxides of nitrogen. Also the high voltage discharge of hydrogen is not so severe.
- **Sulphur hexafluoride:** Electronegative gas used in X-ray equipment, waveguides, coaxial cables, transformers and as an arc-quenching medium in circuit breakers. Dielectric strength is nearly 2.3 times higher than air or nitrogen

2.2.9 Application of dielectrics in transformers

Transformer is basic arrangement of conductors and dielectric insulators. Transformer contains two parts Primary coil and secondary coil.

Energy transforms from primary coil to secondary coil only through magnetic induction, not by any electrical path. So to avoid electrical conduction we must use dielectric insulator at all possible places.

In transformers, the dielectric material is used as insulator as well as cooling agent.

Based on the applications of dielectrics in transformer they fall into three groups.

1. Gaseous dielectric in transformer.
2. Liquid dielectric in transformer.
3. Solid dielectric in transformer.

Gaseous dielectric in transformer

- The usage of nitrogen in transformer prevents oxidation and reduces the rate of deterioration.
- Sulphur hexafluoride dielectric is an electronegative gas which is used in transformer. Itis non-toxic, non-inflammable, and chemically inert.

Liquid dielectric in transformer

- Transformer oil- It is a class of mineral insulating oil and is used as a coolant. It also maintains the insulation of the winding.
- Fluorocarbon liquids are used in large transformer to give high heat transfer rates together with high dielectric strength.

Solid dielectric in transformer

- Fibrous materials are used in air cooled Transformers.
- Cotton tape is used for insulating the conductors of the oil cooled transformers.
- High quality synthetic resin bonded paper in the form of cylinder is used as an insulator between core and coils and also between primary and secondary windings.
- Press board or press paper is used as a filling, and as a packing material between the coils.

2.2.10 Capacitors

- The insertion of a dielectric slab in a capacitor will polarize the charges. The polarization of the charges on either side of the dielectric will produce an electric field in a direction opposite to the applied field.
- A major use of dielectrics is in fabricating capacitors.
- These have many uses including storage of energy in the electric field between the capacitor plates.
- The larger the dielectric constant, the more charge the capacitor can store in a given field, therefore ceramics with non-Centro symmetric structures are commonly used. In practice, the material in a capacitor is in fact often a mixture of several such ceramics.

2.2.11 Electrical Insulation

- **Insulation** is the term used for a variety of materials used to reduce the transfer of energy. Insulation is used around electric wires to protect the wire from the environment or the environment (like people) from the wire.
- High electrical resistivity and low dielectric loss are the most desirable properties here. The most obvious of these uses is insulation for wires, cables etc.,

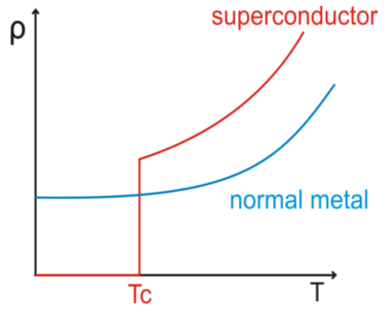
Superconductivity

2.3.1 Introduction to Superconductors:

- The electrical resistivity of all the metals and alloys decreases when they are cooled because the thermal vibrations of the atoms decrease and scattering of electrons is less frequent.
- Any real metal cannot be perfectly pure and will contain some impurities. These impurities are also responsible for electron scattering in the lattice and impurity scattering is more or less independent of temperature.

But certain metals show remarkable behavior i.e. when they are cooled, at a certain low temperature it suddenly loses all of its electrical resistance.

- Superconductivity was first discovered by H K Onnes in 1911 while studying the electrical conductivity of metals at low temperatures. He observed that as purified mercury is cooled, its resistivity vanished abruptly at 4.2K. Above this temperature, the resistivity is small, but finite. The resistivity below this point is so small that it is essentially zero.

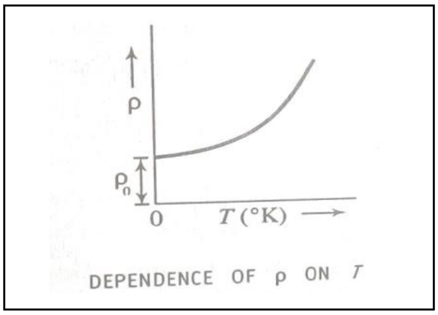


- The temperature at which the transition takes place from normal conducting state to super conducting state is called critical temperature or transition temperature. Denoted as T_c.

- Definition of Superconductivity: Certain metals and alloys exhibit almost zero resistivity (infinite conductivity) when they are cooled to sufficiently low temperature. This phenomenon is called as Superconductivity.
- Superconductor: A material which exhibits superconductivity is called superconductor.
- Superconductivity is reversible. When the superconducting sample is heated, it recovers its normal conducting state at the temperature Tc.
- Properties of Superconductors:
  - Zero electrical resistance:
    The electrical resistance of the superconductor is 0 below the transition temperature.
  - Effect of magnetic field:
    Below the transition temperature of a material, its superconductivity can be destroyed by the application of a strong magnetic field. The minimum magnetic field applied to destroy the superconducting property is called critical field.(Hc)
  - Effect of electric current (Critical current):
    The critical magnetic field required to destroy superconductivity need not necessarily be applied externally. An electric current flowing through the superconducting material itself may give rise necessary magnetic field.
- Persistent Current: When the superconductor in the form of a ring is placed in a magnetic field, then a current is induced in it by electromagnetic induction.
- Since the ring is in superconducting state, the ring has zero resistance. Once the current is set up, it flows indefinitely without any decrease in its value.
- A steady current which flows through a superconducting ring without any decrease in strength as long as the material is in superconducting state is called persistent current.

2.3.2 Temperature dependence of resistivity of a metal:

The electrical conductivity of metal varies with the temperature. The electrical resistance of a metal, to the flow of current, is due to scattering of conduction electrons by lattice vibrations. When the temperature increases the amplitude of lattice vibrations also increases, thereby increasing the resistance. The dependence of resistance of metal (non-superconducting state) on temperature is shown in figure. The resistance decreases with temperature and reaches a minimum value known residual resistance, at T = 0K. The residual resistance at T = 0K is due to impurities in the metal.



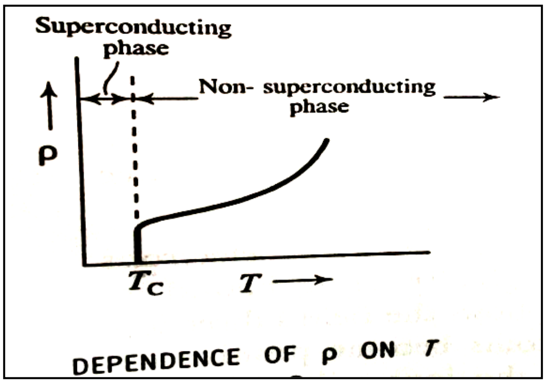
The variation is expressed by Matheissen's rule

$$\boldsymbol{\rho = \rho_o + \rho\,(T)}$$

Where 'ρ' is the resistivity of the given material, 'ρ_o' is the residual resistivity and 'ρ (T)' is the temperature dependent part of resistivity called ideal resistivity.

2.3.3 Temperature dependence of resistivity of a superconductor

The resistance of a superconductor in the non-superconducting state decreases with temperature and the electrical resistivity of some of the metals and alloys vanish entirely below a certain temperature. "The resistance offered by certain materials to the flow of electric current abruptly drop to zero below a threshold temperature. This phenomenon is called **superconductivity** and threshold temperature is called "critical temperature". "The temperature at which a material undergoes transition from normal state to superconducting state losing its resistivity is called the **critical temperature or transition temperature Tc**".

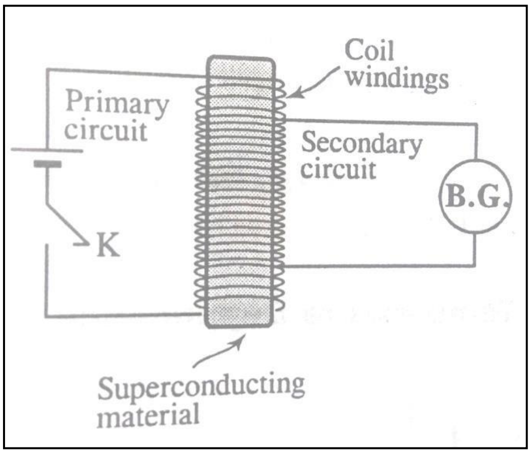


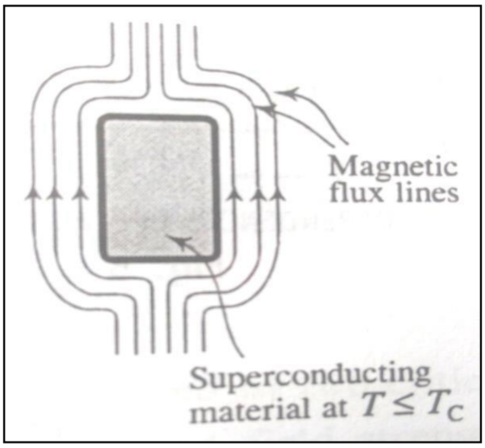
Above the transition temperature, the substance is in the normal state and below it will be in superconducting state. The critical temperature is different for different superconducting materials. It is not very sensitive to the presence of small amount of impurities.

2.3.4 Meissner effect:

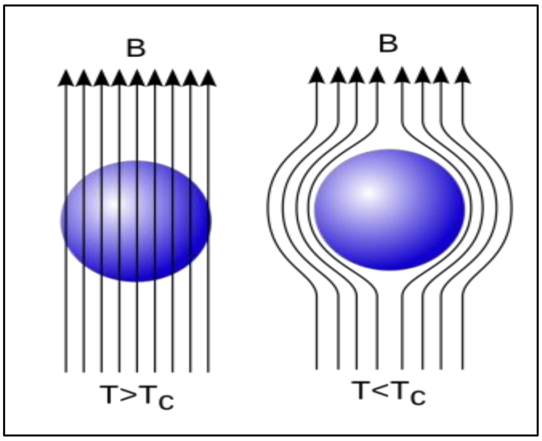
A superconducting material kept in a magnetic field expels the magnetic flux out of its body when it is cooled below the critical temperature and thus becomes perfect diamagnetic. This effect is called Meissner effect. Consider a superconducting material above its critical temperature. A primary coil and a secondary coil are wound on the material (fig.1). The primary coil is connected to a battery and a key K. the secondary coil is connected to a ballistic galvanometer (B.G). When key K is pressed, the primary circuit is closed and a current flows through the primary coil which sets up a magnetic field in it. The magnetic flux instantly links with the secondary coil. This amounts to a change in flux across the secondary coil, and hence a momentary current is driven through the B.G. which shows a deflection. Since the primary current is steady, the magnetic flux will also become steady, and the secondary becomes unchanging. As there is no further change in the flux linkage in the secondary coil, the current will no more be driven in the secondary circuit. Now, the temperature of the superconductor is decreased gradually. As soon as the temperature crosses down the critical temperature, the B.G. suddenly shows a deflection, indicating that the flux linkage with the secondary coil has changed.

The change in flux linkage is attributed to the expulsion of the magnetic flux from the body of the superconducting material as shown in fig





- When a superconducting material in its normal state is placed in a uniform magnetic field, the magnetic lines of force penetrate through the material.
- When the material in a uniform magnetic field is cooled below Tc, the magnetic flux inside the material is excluded or expelled out from the material. Thus, inside superconducting specimen, magnetic induction (B) is 0. This phenomenon is called Meissner effect.



$B_{in} \neq 0$ **$B_{in}=0$**

- A superconductor is a perfect diamagnetic material, with the magnetic susceptibility (χ) equal to -1.
- The flux lines of a magnetic field are ejected out of the superconductor. The specimen acts as an ideal diamagnet. This effect is called Meissner Effect.
- Superconductor is a perfect diamagnet. The magnetic induction (B) inside the specimen is given by,
  $B = \mu_0 (H+M)$
  H – External applied magnetic field
  M – Magnetization produced inside the specimen.
  According to Meissner effect, inside the bulk superconductor B=0
  so, $\mu_0 (H+M) = 0$
  $\mu_0 \neq 0$, $H+M = 0$
  $M = -H$
  Therefore magnetic susceptibility, $\chi = \frac{M}{H} = -1$
  Thus the material is perfectly diamagnetic.

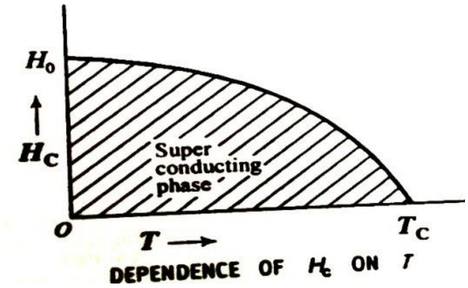
2.3.5 Critical field

Below the transition temperature of a material, its superconductivity can be destroyed by the application of a strong magnetic field. The minimum magnetic field applied to destroy the superconducting property is called critical field. (H_c)

Temperature Dependence of Critical Field:

- The superconducting state of a metal exits only in a particular range of temperature and field strength. The condition for the superconducting state to exist in the metal is that some combination of temperature and field strength should be less than a criticalvalue. Super conductivity will disappear if the temperature of the specimen is raised above itsTc or if sufficiently strong magnetic field is employed. “The minimum magnetic field required to destroy the superconductivity in the material is called critical field Hc”.
- The critical field as a function of temperature is nearly parabolic and can be reasonably represented by
- $\boldsymbol{H}_c = H_0(1 - \frac{T^2}{Tc^2})$

  Where Ho is the critical magnetic field at 0˚ K



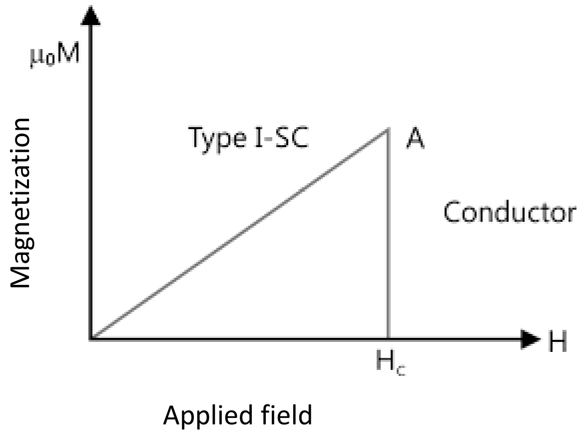
- By applying magnetic field greater than Ho, the material can never become superconductor whatever may be the low temperature. The critical field need not be external but large current flowing in superconducting ring itself can produce critical field and destroys superconductivity.

2.3.6 Types of Superconductors:

The superconductors can be classified into two distinct groups according to their behavior in external magnetic field:

1. **Type- I Superconductors:**

- The superconductors in which the magnetic field is totally excluded from the interior of superconductors below a certain magnetizing field H_c and at H_c the material loses superconductivity and the magnetic field penetrates fully are called as type I or soft superconductors.
- Ex: Tin, Lead, Aluminum, Mercury, Zinc, Magnesium, etc.
- The magnetization curve for type I superconducting materials is shown below

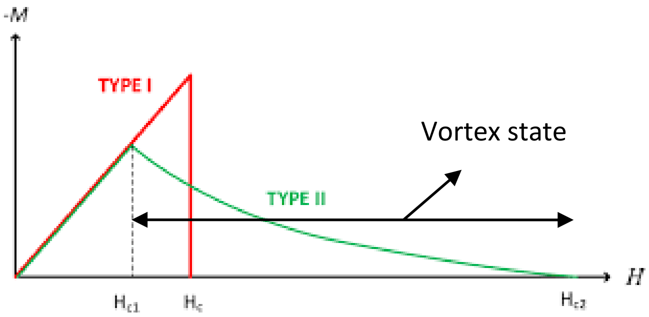


- Characteristics of Type I superconductors are:

1) They exhibit or obey complete Meissner effect.
2) The critical values of magnetic field H_c at which magnetization drops are very low. The maximum known critical field for type I superconductors is of the order of 0.1T.The low value of H_c makes those materials unsuitable for their use in high field superconducting magnets.
3) The magnetization curve shows transition at H_c is reversible. This means that if the magnetic field is reduced below H_c, the material again acquires superconducting property and the field is expelled.
4) Below H_c the material is superconducting and above H_c it becomes a conductor.

2. <u>Type - II superconductors:</u>

- The superconductor in which the material loses magnetization gradually rather than suddenly is termed as type II or hard superconductors.
- The magnetization curve for these superconductors is shown in figure below



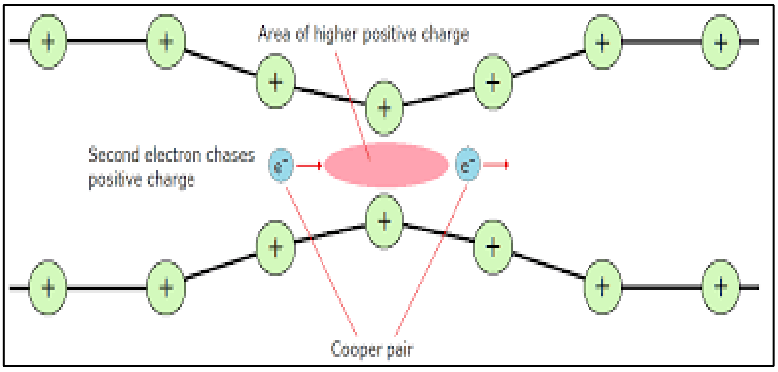
- Characteristics of type II superconductors are:
    - They do not show complete Meissner effect.
    - These superconductors have 2 critical fields. H_{c1} – the lower critical field and H_{c2} – the upper critical field.
    - The specimen is diamagnetic below H_{c1}, i.e. the magnetic field is completely excluded below H_{c1}.
    - At H_{c1} --- the flux begins to penetrate the specimen and penetration of flux increases until the upper critical field H_{c2} is reached.
    - At H_{c2} --- the magnetization vanishes and specimen returns to the normal conducting state.
    - The value of H_{c2} is greater than H_c.
      The materials which display type II behavior are essentially inhomogeneous and include Nb-Zr, Nb-Ti, alloys and Va-Ga and Nb-Sn inter metallic compounds.
    - These are more useful than type I superconductors due to tolerating high magnetic fields.

2.3.6 <u>BCS Theory (Qualitative):</u>

- Bardeen, Cooper and Schrieffer (BCS) in 1957 explained the phenomenon of superconductivity based on the formation of cooper pairs. It is called BCS theory.
- It is a quantum mechanical concept. During the flow of current in a superconductor, when an electron approaches a positive ion lattice of the metal there is a Coulomb force of attraction between the electron and the lattice ion and thus ion core is set in motion causing lattice distortion.
- Smaller the mass of the positive core, larger will be the distortion. The lattice vibrations are quantized in a terms of Phonons. Now another electron passing by this distorted lattice will interact with it and thus the energy of this electron is also reduced.
- This interaction is looked upon as if the two electrons interact via the phonon field, (because the lattice vibrations are quantized and quanta of these vibrations are phonons) resulting in lowering of energy for the electrons. Due to this interaction an apparent force of attraction develops between the electrons and they

tend to move in pairs. This interaction is strongest when the two electrons have equal and opposite spins and momentum.

- This leads to the formation of cooper pairs. “Cooper pairs are a bound pair of electrons formed by the interaction between the electrons with opposite spin and momentum in a phonon field”.
- At normal temperatures the attractive force is too small and pairing of electrons does not take place. At lower temperature, that is below the critical temperature the apparent force of attraction exceeds the Coulomb force of repulsion between two electrons leading to the formation of cooper pairs.
- According to quantum mechanics a cooper pair is treated as single entity. A wave function is associated with each such cooper pair and wave functions associated with similar cooper pairs start overlapping which extends over a million pairs and hence virtually over the entire volume of the superconductor.
- Finally large number of cooper pairs forms a union one aiding the motion of the other. So the entire union of cooper pairswill therefore move as one unit. The resistance experienced by any one cooper pair is overcome by the co-operative action of the other pairs in the union.
- Ultimately when electrons flow in a material in the form of cooper pairs do not encounter scattering. The resistance vanishes and conductivity is very large and thus the phenomenon superconductivity.



Formation of cooper pairs

2.3.7 <u>High temperature superconductivity:</u>

- Super conductors whose critical temperature is greater than 20k are called high temperature superconductor or high T_c superconductors.
- High temperatures superconductors are not metals and inter metallic compounds, but are oxides that fall under the category of ceramics. Most of them are based on copper oxides with other metallic elements.
- High temperature super conductors have a complex unit cell structure with oxygen. Such cells are made of 1 atom of rare earth metal, 2 barium atoms, 3 copper atoms and 7 oxygen atoms. Such compounds are popularly referred to as 1-2-3 superconductors.
- Eg: $Y_1Ba_2Cu_3O_7$[Yttrium, Barium, Copper and oxygen] having T_c=90k.
- Later other two compounds developed without a rare earth element and with different cell structure than 1-2-3 super conductors.
- Eg: Bismuth, Strontium, Calcium, copper and oxygen at T_c= 100kHigh temperature super conductivity cannot be explained on the basis of BCS theory.

2.3.8 <u>DC and AC SQUIDs (Qualitative):</u>

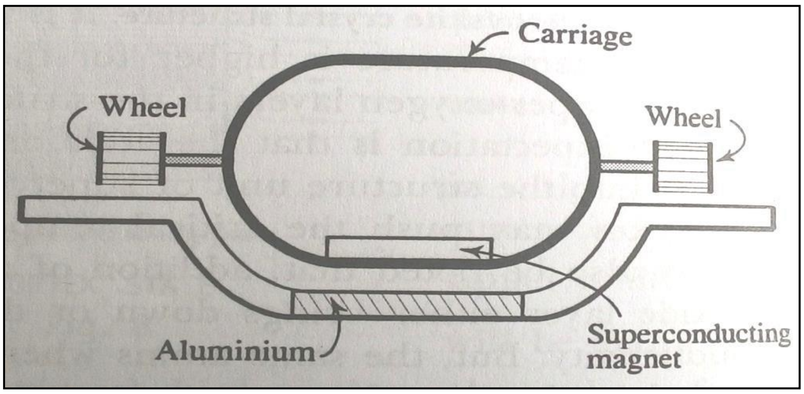
➢ The SQUID (Superconducting Quantum Interference Device) is a double-junction quantum interferometer formed from two Josephson junctions mounted on a superconducting ring. Magnetic field is applied normal to the plane of the ring.

➢ It is a very sensitive magnetometer used to measure extremely subtle magnetic fields.

- SQUIDs are sensitive enough to measure fields as low as 5×10^{-14} T. Their noise levels are low. For comparison, a typical refrigerator magnet produces 0.01tesla (10^{-2} T), and some processes in animals produce very small magnetic fields between 10^{-9} T and 10^{-6} T.
- A SQUID consists of tiny loops of superconductors employing Josephson junctions to achieve superposition: each electron moves simultaneously in both directions. Because the current is moving in two opposite directions.
- There are two main types of SQUID: direct current (DC) and radio frequency (RF)

2.3.9 <u>Construction and working of MAGLEV Vehicle</u>

Magnetically levitated vehicles are called Maglev vehicles. They are made use of in transportation by being set afloat above a guideway. The utility of such levitation is that, in the absence of contact between the moving and stationary systems, the friction is eliminated. With such an arrangement great speed is achieved with very low energy consumption. The phenomenon on which the magnetic levitation is based is Meissner effect.



The vehicle consists of superconducting magnets built into its base. There is an aluminum guide way over which the vehicle will be set afloat by magnetic levitation. The magnetic levitation is brought about by enormous repulsion between two highly powerful magnetic fields; one produced by the superconducting magnet inside the vehicle, and the other one by the electric currents in the aluminium guide way.

During the motion of the vehicle, it is enough if that part of the guideway over which the vehicle is located, is activated instantaneously. For this reason, guide way is formulated in terms of a number of segments provided with coils. The flow of currents through the coils could be related to the position and instantaneous speed of the vehicle. The currents in the guide way no only produce the necessary magnetic field to levitate the vehicle but also help in propelling the vehicle forward.

The vehicle is also provided with retractable wheels. The wheels almost serve the same purpose as those of an airplane. With the wheels, the vehicle runs on the guide way the way the airplane does during the take off. Once it is levitated in the air, the wheels are retracted into the body. The height at which the vehicle is levitated above the guide way is about 10 to 15 cm. While stopping, the wheels are drawn out and the vehicle slowly settles on the guide way by running over a distance, as an airplane does while landing.