SUPERCONDUCTING MATERIALS

- ***Superconductivity*** is a phenomenon in which certain metals, alloys & ceramics conduct electricity without resistance when, it is cooled below a certain temperature called the critical temperature.
- Superconductivity was discovered by a Dutch Physicist, **Heike Kammerlingh Onnes in 1911** & it is still an exciting field of discovery & Technological applications. This new state was first discovered in **Mercury when cooled below 4.2 K**. Since then a large number & wide variety of metals, alloys, binary & ternary chemical compounds have been found to show superconductivity at different temperatures.
- **Superconductor**

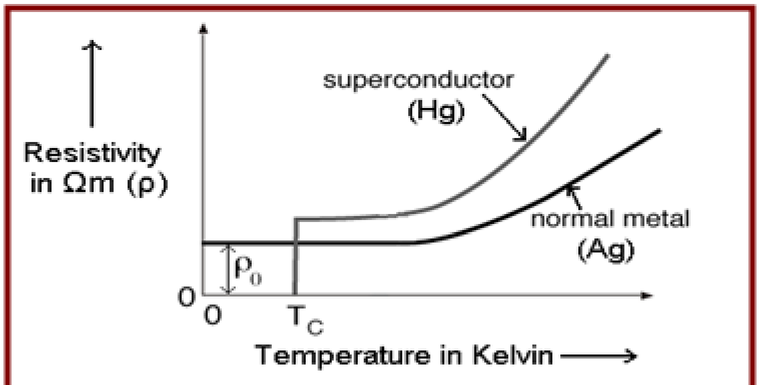
  A Superconductor is a material that loses all its resistance (offers zero resistance) to the flow of electrical current, when it is cooled below a certain temperature called critical temperature or transition temperature T_C.

  Examples:

  Mercury (Hg), Zinc (Zn), Vanadium (V), Tin (Sn) & Niobium (Nb).

- **Critical Temperature Tc (Transition Temperature)**
- The temperature at which a material's electrical resistivity drops to absolute Zero is called the critical temperature or Transition temperature Tc.
- At & below Tc the material is said to be in the superconducting state & above this temperature, the material is said to be in Normal state.

- From Figure it can be seen that, the electrical resistivity of normal metal decreases steadily as the temperature is decreased & reaches a low value of at 0K called the residual resistivity ρ_0. But in contrast, the electrical resistivity of mercury suddenly drops to Zero at critical temperature Tc & is 4.2K for Hg.



Electrical resistivity Vs temperature plots for a superconductor and a normal metal

- Below the critical Temperature, not only does the superconductor suddenly achieve Zero resistance, it exhibits a variety of several astonishing magnetic & electrical properties.
- The Tc value for some selected metals, inter metallic & ceramic superconductors are given in the following table.

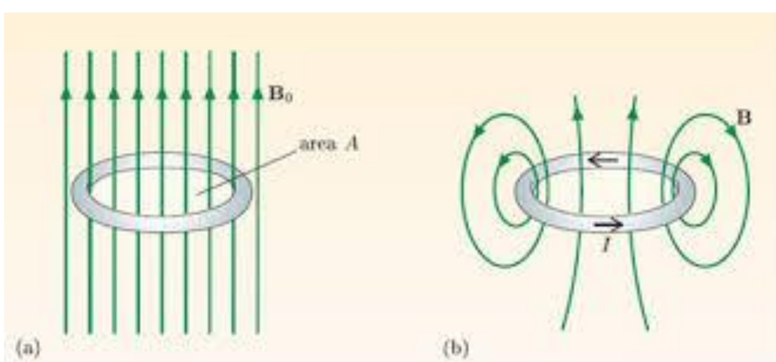
Metals	T_c in K	Inter metallic compounds	T_c in K	Ceramic compound	T_c in K
Tin (Sn)	3.72	NbTi	9.5	$Y_1Ba_2Cu_3O_{7-x}$	93
(Hg)	4.2	Nb_3Sn	21	Ti-Ba-Ca-Cu	125
(V)	5.3	Nb_3Ge	23.2	HgBaCuO	133

- **Properties of Superconductors:**

Few Important properties of superconductors are explained in brief in this section.

1. ***Electrical resistance,***

- The resistance of superconducting material is very low & is the order of 10^{-7} Ωm.
- A super conductor is characterized by zero electrical resistivity. It is not fundamentally possible to test experimentally whether the resistance is zero. A method devised by Onnes consists of measuring the decrease of the current in a closed ring of superconducting wire.
- The superconducting ring is kept in a magnetic field and it is cooled to below the critical temperature so that it goes into the superconducting state.
- When external magnetic field is switched off, a current induced in the ring.
- If the ring had a finite resistance, R the current circulating in the ring would decrease according to the equation: $I(t) = I(0)\, e^{-Rt/L}$ ……..(1)



2. ***Effect of impurities***

- When impurities are added to superconducting elements, the superconducting property is not lost, but the Tc value is lowered.

3. **Effect of pressure & stress**

- Certain materials are found to exhibit the superconductivity phenomena on increasing the pressure over them. For example, cesium is found to exhibit superconductivity phenomena at Tc = 1.5K on applying the pressure of 110Kbar.
- In superconductors, the increase in stress results in increase of Tc value.

4. ***Isotope effect***

- The critical temperature of superconductor is found to vary with its isotopic mass. This variation in Tc with its isotopic mass is called the isotopic effect.

$$T_c \;\alpha\; 1/(M)^{1/2}$$

Where, M is the isotopic mass

i.e. the transition temp is inversely proportional to the square root of the isotopic mass of a single superconductor.

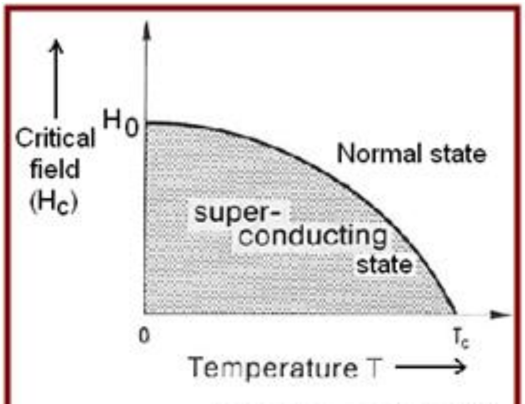
5. ***Critical Magnetic field***

- If sufficiently strong magnetic field applied to a superconductor at any temperature below its critical temperature, the superconductor found to undergo a transition from the superconducting state to the normal state.
- This minimum magnetic field required to destroying the superconducting state is called the critical magnetic field Hc.
- The critical magnetic field of a superconductor is a function of temperature. The variation of Hc with Temperature is given by
-

$$H_c = H_0[1-(T/T_c)^2]$$

Where H_0 is critical field at T=0 K

- The critical field decreases with increasing temperature and, becoming Zero at T=Tc.
- Figure shows the variation of Hc as a function of Temp. The material is said to be in superconducting state within the curve & is non superconducting in the region outside the curve.



Dependence of H_c on T

6. Critical current density Jc & Critical current Ic

- The critical current density is another important characteristic feature of the superconducting state.
- When a current density through a superconducting sample exceeds a critical value Jc, the superconducting state found to disappear in the sample.
- This happens because, the current through the superconductor itself generates a magnetic field, & at a sufficiently high current density the magnetic field will start exceeding a critical magnetic field Hc thereby making a superconducting state to disappear in the material.
- Hence, ***the critical current density can be defined as the maximum current that can be permitted in a super conducting material without destroying its superconducting state.*** The critical current density is a function of Temperature, i.e. colder the temperature for a superconductor, the more is the current it can carry.
- For a long cylindrical superconducting wire of radius r, the relation between critical current Ic & Magnetic field Hc is given by..

  Ic =2πrHc

- Similarly, the relation between Jc & Ic is given by

  Jc = Ic/A

  Where, A is the superconducting specimen's cross-sectional area.

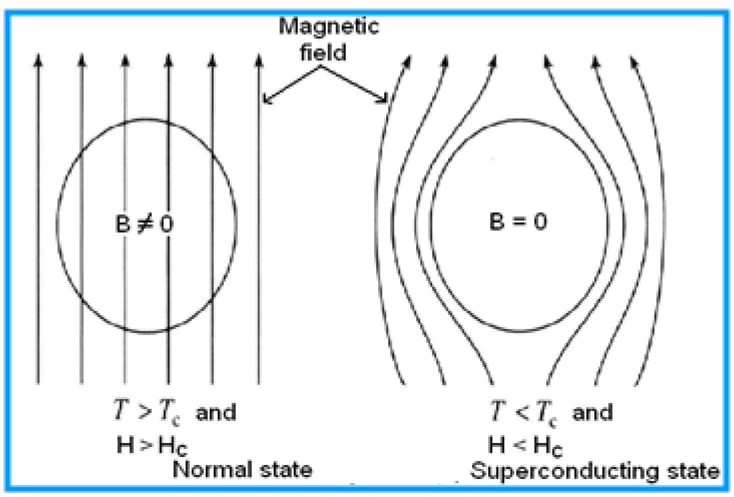
7. Persistent current

- When current is made to flow through a superconducting ring (say a loop of lead wire) which is at a temperature either equal to its Tc value or less than its Tc value, it was observed that the current was flowing through the material without any significant loss in its value.
- This steady flow of current in a superconducting ring without any potential deriving it, is called the Persistent current.

- The persistent current does not need external power to maintain it because there do not exist I^2R losses.
- 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.

8. ***Meissner effect (Diamagnetic property)***

- The complete expulsion of all the magnetic field by a superconducting material is called the "**Meissner effect**"
- When a superconducting material is placed in a magnetic field (H>Hc) at room temperature, the magnetic field is found to penetrate normally through the material.
- In 1933 Meissner and Robort Ochesenfeld found that 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**. This effect is reversible. When the temperature is raised from below TC, the flux suddenly penetrates the specimen at T = Tc and the material returns to the normal state.



- **<u>To prove χ_m = -1 for superconductors</u>**

We know that, for magnetic materials the magnetic induction or magnetic flux density B is given by

$$B = \mu_0 (M+H) \quad \text{........(1)}$$

Where, μ_0 is the permeability of free space

M is the intensity of the Magnetization

& H is the applied magnetic field.

- But, we know that for a superconductor **B=0(above figure)**, Therefore, equation (1) can be written as

$$\mathbf{0 = \mu_0 (M+H)}$$

Because, $\mu_0 \neq 0$

$$\mathbf{M+H = 0} \quad \underline{\textbf{OR}} \quad \mathbf{M= -H} \quad \underline{\textbf{OR}} \quad \mathbf{(M/H) = -1}$$

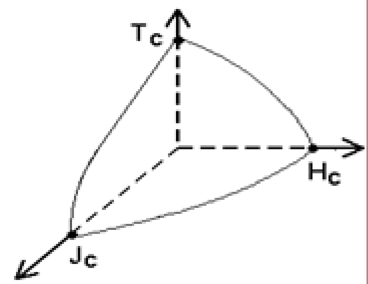
- Hence, $\chi_m = M/H$ is called the magnetic susceptibility.
- Thus, this means that, for a superconductor the susceptibility is negative & maximum. i.e. a superconductor exhibits perfect diamagnetism.

- **<u>Three important factors to define a superconducting state:</u>**

  In general, the superconducting state is defined by three important factors,

1. Critical temperature Tc.
2. Critical current density Jc.
3. Critical magnetic field Hc.

- Each of above three parameters is very dependent on other two properties. To sustain superconducting state in a material it is required to have all three factors, current density, magnetic field and the temperature, to remain below their critical values; & all of which depend on the material.
- The relation between Tc & Jc is shown in the phase diagram figure below.
- The highest values for Hc & Jc occur at 0K, while the highest value for Tc occurs when H & J are Zero. Thus, the plot of all these three parameters represents a critical surface.
- Within the surface the material is superconducting & outside the surface the material is said to be in normal state.



Critical surface
phase diagram

London Penetration Depth:

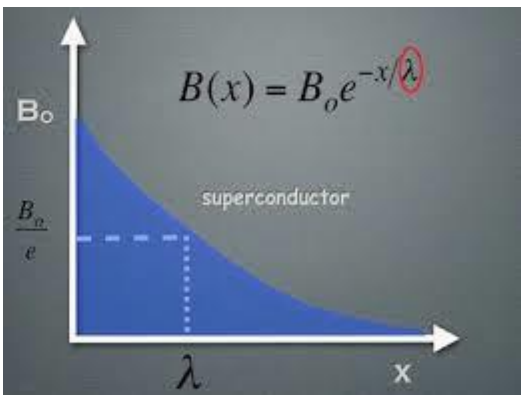
- When a magnetic field is applied to a superconductor, the applied field does not suddenly drop to zero at the surface. Instead the field decays exponentially according to the formula

$$H(x) = H(0)\, e^{-x/\lambda}$$

- Where H(0) is the field applied at the surface at x=0 and x is the distance from the surface. The length λ is called the London Penetration depth. It may be defined as the effective depth to which a magnetic field penetrates a superconductor. The penetration depth λ is temperature dependent and is given by following relation,

$$\lambda(T) = \frac{\lambda(0)}{[1 - (T/T_c)^4]^{1/2}}$$

Where $\lambda(T)$ and $\lambda(0)$ are penetration depths at T and 0K.



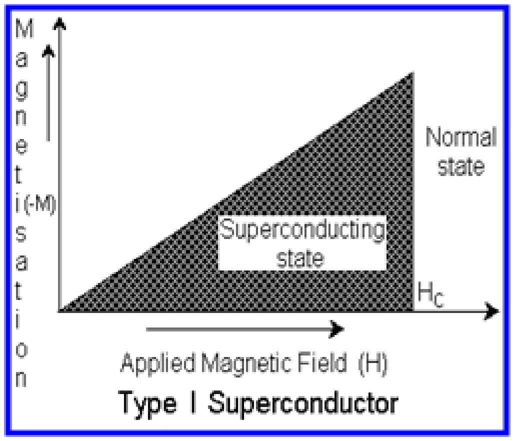
- It follows from the equation that λ increases with the increase in temperature and at the critical temperature, it becomes infinite. At T = Tc the material goes into the normal state and hence the magnetic field penetrates the whole specimen.

Types of Superconductors:

- Based on the behavior of superconducting materials in an applied magnetic field, the superconductors are classified into type I & II superconductors.

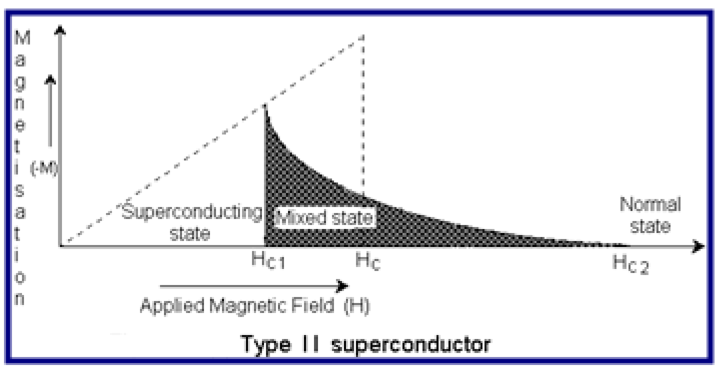
Types I Superconductors:

- Type-I superconductors exhibits complete Meissner effect, i.e. they are completely diamagnetic. The values of Hc for type I superconducting materials are always too low.
- The magnetization curve shows that, the transition at Hc, is reversible.
- Type I superconductors are also called as **Soft superconductors** because of their tendency to allow the field penetration even for a lower applied field.



Type II Superconductors:

- Type II superconductors behaves differently in an increasing field as shown in figure for an applied field below H_{cl}, the material is perfectly diamagnetic & hence the field is completely excluded. H_{cl} is called as lower critical field and H_{c2} is called the upper critical field.
- In the region between H_{c2} & H_{cl} the material is in the mixed state or vortex state. The value of H_{c2} for type II may be 100 times more or even higher than that of type I superconducting materials.



- As H_{c2} & Tc of type II superconducting materials are higher than that of type I superconductors, the type II superconducting materials are most widely used in all engineering applications.
- Type II superconducting materials are also called **hard superconductors** because of relatively large magnetic field require to bring them back to their normal state.

Type-I Superconductors		**Type-II Superconductors**	
Material	**H_c in Tesla**	**Material**	**H_c in Tesla**
Ta	0.083	$Y_1Ba_2Cu_3O_7$	300
Pb	0.08	$Ba_{2-x}B_xCuO_4$	150
Hg	0.014	Nb_3Sn	24.5
Sn	0.030	Nb_3Ge	38

Comparison between Type I & Type II Superconductors:

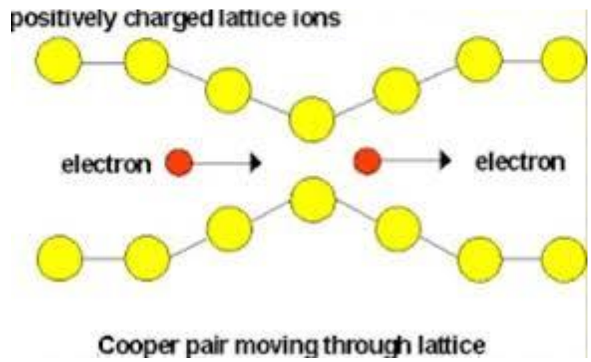
Type I superconductor	Type II superconductor
■ These superconductors are called soft superconductors. ■ Only one critical field (H_C) exists for these superconductors. ■ The critical field value is very low. ■ This superconductor exhibits perfect & complete Meissner effect. ■ These materials have limited technical applications because of very lower field strength value. Ex. Pb, Hg, Zn etc.	■ These superconductors are called as hard super conductors. ■ Tow critical field H_{c1} & H_{c2} exist for these superconductors. ■ The critical field value is very high. ■ These do not exhibits perfect & complete Meissner effect. ■ These materials have wider technological applications because of very higher field strength value. Ex. Nb_3Ge, Nb_3Si, $Y_1Ba_2Cu_3O_7$ etc.

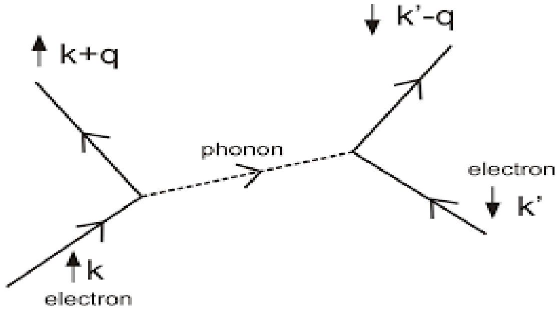
BCS Theory:

- In 1957, the American physicists J Bardeen, L.N.Cooper and J R Schrieffer developed the quantum theory of superconductivity, which came to be known as BCS theory.
- Starting from the two experimental results, namely the isotope effect and the variation of electronic specific heat with temperature, the BCS theory assumed interaction of two electrons through quanta of lattice vibrations.
- The two principle features of BCS theory are:

  (1) Electrons form pairs, called COOPER PAIRS, which propagates throughout the lattice and

  (2) Such propagation is without resistance because the electrons move in resonance with phonons.
- To appreciate the formation of Cooper pair, let us consider the model in Figure given below, in which two electrons propagate along a single lattice row. Each electron experiences an attraction towards its nearest positive ion. When the electrons get very close to each other in the region between ions, they repel each other due to Coulomb force.
- In an equilibrium condition, a balance between attraction and repulsion is established and the two electrons combine to form a Cooper pair. The electrons entering into such interaction should have equal and opposite spins and their energies are the same. Due to conductivity increases infinitely, all the cooper pairs of electrons move coherently.





- At normal temperatures, the attractive force is too small and pairing of electrons does not take place. However, at lower temperatures, such pairing is energetically advantageous.

High Temperature Superconductors:

- Based on the coolants to achieve superconductivity phenomena in materials, the superconductors fall in two Categories:

  1. Low temperature superconductors.

  2. High temperature superconductors.

➢ **Low temperature superconductors:**

- Superconductors that require liquid helium as coolant are called as low temperature superconductors (LTS OR Low - Tc). Liquid Helium temperature is 4.2K above Absolute Zero.

➢ **High Temperature superconductors:**

- **Superconductors having their Tc values above the temperature of liquid Nitrogen (77K or -196˚C) are called the high temperature superconductors (HTS or Low-Tc).**
- After the discovery of superconducting In mercury (4K) by Heike Kammerling Onnes, the critical temperature had been gradually increased from 4K of Hg to 23K in the compound Nb3Ge first discovered in 1973.This remained a record until 1986.
- On January27, 1986, A new era of superconductivity science & Technology begin. J. George Bednorz & K.A.Muller using a variant of the materials synthesized by Michel, smashed the long stand 23K temp. record with a compound of barium, lanthanum, copper & oxygen that at 30K is a very indicator of superconductivity.

- Similar materials with higher transition temp. (High-Tc) soon followed in the history of superconductors when $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) or the so called 1-2-3 compound was discovered in 1987. The 1-2-3 compound was the first oxide superconductor to have transition temperature above liquid nitrogen temperature.
- The highest transition temp currently known in 138K in a thallium doped mercuric cuprate comprised of the elements Hg,Tl, Ba,Ca,Cu, & oxygen.
- Examples for High temp superconductors are listed in Table 12.2.

Material	**Tc' s in K**
1. $Pb_2YSr_2Cu_3O_8$	77
2. Y-Ba-Cu-O($Y_1Ba_2Cu_3O_7$)	93-95
3. Tl(Bi)-Ba(Sr)-Ca-Cu-O	122-125
4. Hg-Ba-Ca-Cu-O	130-135

Applications of superconductors

➢ **Magnetic levitation (Maglev)**

- Magnetic levitation or maglev is the process by which an object is suspended above another object with no other support but magnetic fields.
- We know that, a diamagnetic substance repels a magnetic field. Thus, the perfect diamagnetic property of superconductors make them suitable for achieving friction less motion in motors & bearing.
- The phenomenon of magnetic levitation is based on Meissner effect.
- **<u>How to achieve magnetic levitation?</u>**
- The magnetic levitation is brought about by enormous repulsion between two highly powerful magnetic fields. If a small magnet is brought near a superconductor it will be repelled. This repulsion takes place due to the induced currents in the superconductor which is being generated by the magnetic field of the magnet. Because of zero resistant property of the superconductor this current persists and thus, the field due to this induced current repels the field due to the magnet. As a result, the magnet floats freely (i.e., levitated) above the superconductor.
- Thus, the levitation of the magnet or maglev demonstrates two critical properties of superconductors

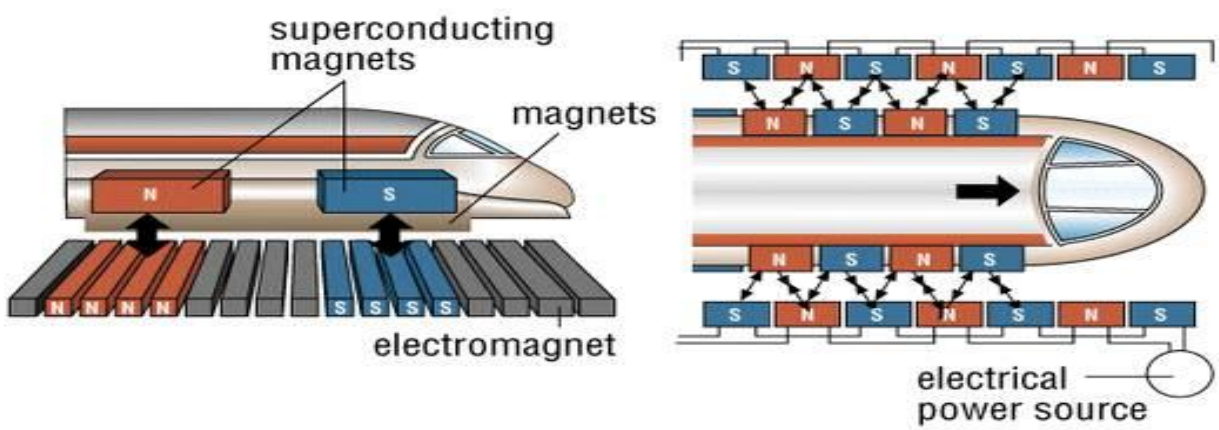
(i) Zero resistance and

(ii) Meissner effect.

Applications:

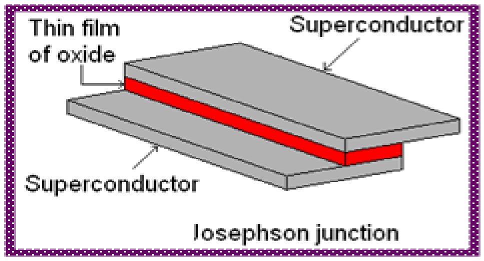
- Magnetically levitated vehicles are called maglev Vehicles. The utility of such levitation in vehicles is that, in the absence of contact between the moving & stationary systems, the friction is eliminated. With such an arrangement great speeds could be achieved with very low energy consumption.

- **Maglev train**
- The levitation is based on two techniques
  (1) Electromagnetic suspension (EMS)
  (2) Electrodynamics suspension (EDS)



- In attractive EMS the electromagnets installed on the train bogies attract the iron rails (guide ways). The vehicle magnets wrap around the iron guide ways & the attractive upward force lifts the train.
- In EDS levitation is achieved by creating a repulsive force between train & guide ways.
- The basic idea of maglev train is to levitate it with magnetic fields so that there is no physical contact between the train & the rails (guide ways).
- Consequently the maglev train can travel at very high speed. These trains travel at a speed of about 500 Km/hrs.
- A similar magnetic propulsion system is being used to launch the satellite into orbits directly from earth without the use of Rockets.

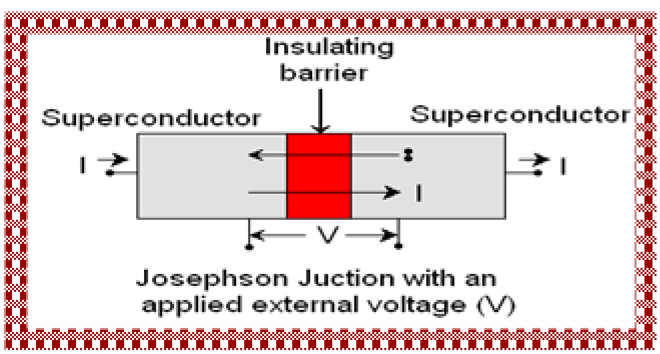
- **Josephson effect & its Application:**



Josephson Effect:

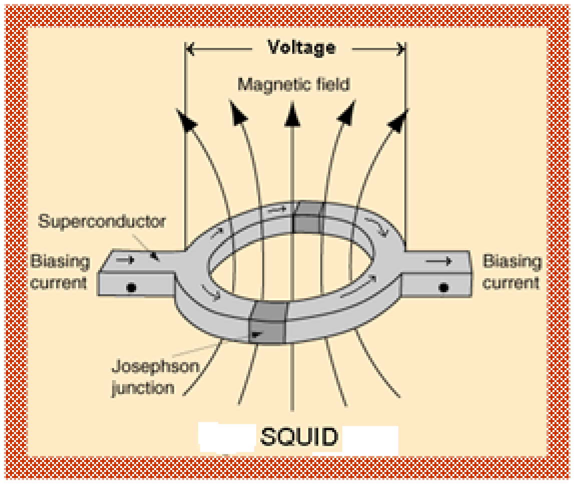
- The wave nature of moving particles makes the electrons to tunnel through the barrier (Insulator), i.e. the electrons can tunnel from one superconductor to the other. As a consequence of the tunneling of electrons (copper pairs) across the insulator, there is a net current across the junction. This is called as d.c. Josephson effect. The current flows even in the absence of a potential difference.
- The magnitude of the current depends on, the thickness of the insulator, the material nature & on the temperature. On the other hand, when a potential difference V is applied between the two sides of the junction Fig.12.8, there will be an oscillation of the tunneling current with angular frequency v=2eV/h. This is called the **a.c. josephson effect**. Thus, according to a.c. josephson effect, the junction generates an a.c current at frequency of **2eV/h** Hz/volts.

- **Josephson junction:** Two superconductors separated by a very thin strip of an insulator.



Application of Josephson junction:

- Josephson junctions are used in sensitive magnetometers called SQUID-Superconducting Quantum Interference Device. A SQUID is formed by connecting two Josephson junctions in parallel.



- When current is passed into this arrangement, the current splits flowing across the two opposite arc. The current through the circuit will have a periodicity which is very sensitive to the magnetic flux passing normally through the closed circuit. As a result, extremely small magnetic flux can be detected with this device.

  This device can also be used to detect voltages as small as 10^{-15} volt.

  Magnetic field changes as small as 10^{-21} T can be detected.

  Weak magnetic fields produced biological currents such as those in the brain can also be detected using SQUID's.

  SQUID detectors are used to measure the levels of the iron in liver, so that the iron built up can be treated before much harm is done to the body.

- **<u>Other applications of Superconductors:</u>**

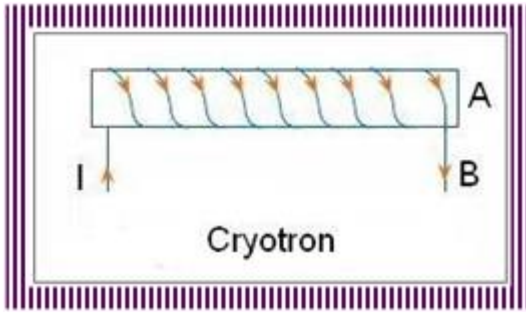
➢ Superconductors can be used to transmit electrical power over very long distances, without any power loss or any voltage drop.

1. Superconducting generators has the benefit of small size & low energy consumption than the conventional generators.
2. Superconducting coils are used in N.M.R (Nuclear Magnetic Resonance). Imaging equipments which are used in hospitals, for scanning the whole body to diagnose medical problems.
3. Very strong magnetic fields can be generated with coils made of high-Tc superconducting materials.
4. Superconductors can act as relay or switching system in a computer. They can also be used as memory or storage element in computers.

Cryotron:

It is a relay or switch made of superconductors whose size can be made very small. In addition, these switches consume a very little current.

The cryotron consists of two superconducting materials A & B. Let the material A be inside the coil of wire B as shown in figure.



- Let the critical field of the material A be H_{CA} & that of B be H_{CB} respectively and also, let $H_{CA} < H_{CB}$. If a current I is passed through the material B, The current induces a magnetic field H. If this induced field H happens to be greater than H_{CA} then the superconducting property of the material A gets destroyed.
- Hence, the resistivity increases & the contact is broken. Thus, the current in A & B can be controlled by the current in B & hence, this system can act as relay or switch element.
- Very fast & accurate computers can be constructed using super conductors & the power consumption is also very low.
- Ore separation can be done efficiently using superconducting magnets.

…Best of Luck…