SUPERCONDUCTIVTY

The phenomenon by virtue of which certain materials exhibit zero resistivity or infinite conductivity when cooled below a certain temperature is called ‘superconductivity’. The materials which show the property of superconductivity are known as superconductor.

The best known conductors of electricity like silver and copper cannot be come superconductors. Whereas compounds and alloys of some metals, non-metals and ceramics etc., become superconductors when cooled below the critical temperature.

Example:

Elemental superconductor: Hg = 4.15K, Pb = 7.19K

Compound Superconductor : $AlNb_3$ = 19K, $GeNb_3$ = 23K

Ceramic Superconductor” $HgBa_2Ca_2Cu_2O_8$ = 133K, $Ti_2Ba_2Ca_2Cu_2O_{11}$ = 125K

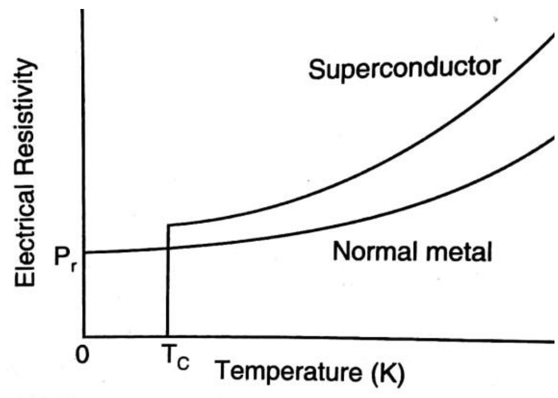
General properties of superconductors:

1) It is a low temperature phenomenon. Below the critical temperature transition from normal state to super conducting state takes place. The transition temperature is different for different materials.
2) Resistance of a superconductor is zero.
3) Superconductivity occurring in metals having valance electrons from 2 to 8. Mono valence metals are not superconductors. E.g. Cu, Ag.
4) Superconducting elements generally lie in the inner columns of the periodic table.
5) Transition metals having odd number of valance electrons i.e. 3, 5, 7 are favorable to exhibit superconductivity more than the metals having even number of valance electrons 2, 4, 6.
6) Ferromagnetic (Fe, Co, Ni) and anti ferromagnetic (Co O, Ni O) materials are not superconductors.
7) Super conductors do not allow magnetic field through them. They are perfectly diamagnetic in nature.
8) Superconductivity vanishes if the current in the superconductor increases beyond the critical current I_C.
9) Superconductivity disappears if the applied magnetic field exceeds the critical field H_C.
10) Thermal conductivity of superconductors is very low which indicates that superconducting electrons has no role in heat transfer.
11) Specific heat of superconductors increase discontinuously.
12) Prominent examples of superconductors include aluminium, niobium, magnesium diboride, cuprates such as yttrium barium copper oxide and iron pnictides. These

materials only become superconducting at temperatures below a certain value, known as the critical temperature.

13) Some elements like Bismuth, Antimony etc., become superconducting under high pressure.

Critical temperature (Tc)



The temperature below which a substance behaves like a superconductor is known as ‘critical temperature’ or ‘transition temperature’ (T_C), it is different for different materials.

If we draw a graph by taking temperature along X-axis and corresponding resistivity along Y-axis the nature of the graph will be like as in the figure.

From the figure it is clear that the resistivity drop suddenly at Tc to zero. If we cool below Tc then the material exist in superconducting state and above Tc the material exist in normal state.

Effect of magnetic field on superconductivity:

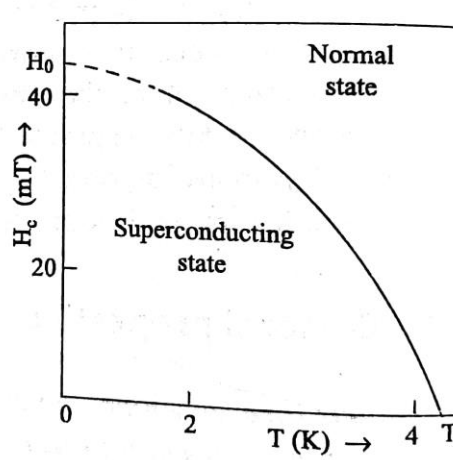
Superconductivity disappears by the application of strong magnetic field. The minimum magnetic field required to destroy superconductivity is called critical field (H_C). The value of critical field depends on the temperature of the material.

At T = Tc, Hc = 0. At temperature below Tc, Hc increases. The dependence of critical field upon the temperature is given by

$$H_C(T) = H_C(0)(1 - \frac{T^2}{T_C{}^2})$$

Where $H_C(0)$ is the critical field at 0^0K

Hc(T) Critical field at T^0C, Tc is the critical temperature



If we draw a graph by taking T along X-axis and H along the Y-axis the nature of the graph will be like in figure. Right to T_C and above $H_C(0)$, the material exists in normal state and below T_C and $H_C(0)$, material in superconducting state.

From the figure it is clear that, If H <$H_C(0)$, the material is in superconducting state. And if H> $H_C(0)$, the material is in normal state.

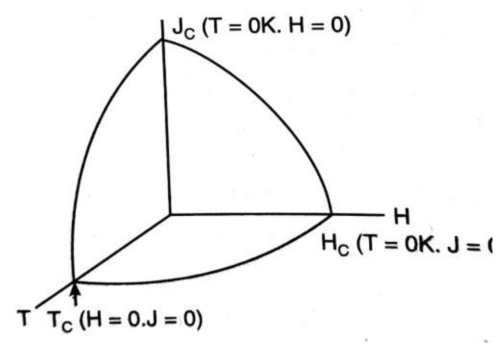
Critical current density

The maximum current density at which the superconductivity disappears is called the critical current density Jc. If the value of J is less than Jc then the current can sustain itself where as if j > Jc the current cannot sustain itself.

A superconducting ring of radius r ceases to be a superconductor when the current is

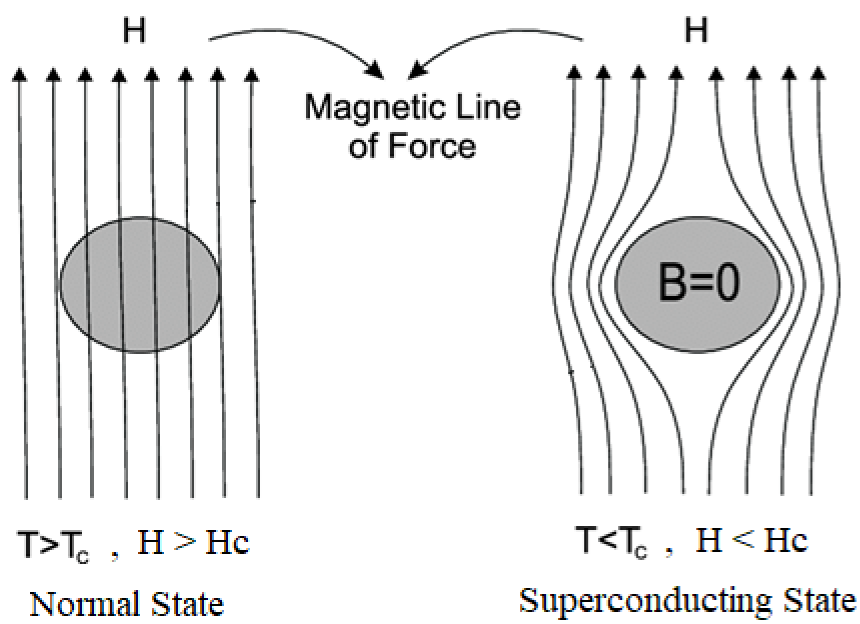
Effect of current $I_C = 2\pi r H_C$

As the temperature of the superconductor increases the current carrying capacity decreases and falls to zero at transition temperature. The variation of critical current Jc, critical magnetic field Hc with temperature is shown in the figure.



Missner Effect:

If a superconducting material is placed in a magnetic field at H < H_C and T < T_C then the magnetic flux inside the material is excluded from the material. This effect is known as 'Missner effect'.



From Missner effect it is clear that magnetic field inside a superconductor is zero i.e. a superconductor is a perfect diamagnetic substance. Because the magnetic induction $\vec{B}$ inside a material medium is given by

$$\vec{B} = \vec{B}_0 + \mu_0 \vec{M} = \mu_0 \vec{H} + \mu_0 \vec{M} = \mu_0 (\vec{H} + \vec{M}) \text{ since} (\vec{B}_0 = \mu_0 \vec{H})$$

Where $\vec{B}_0$ is the magnetic induction in free space. $\vec{H}$ is the applied magnetic field, $\vec{M}$ is the intensity of magnetization.

Since $\vec{B} = 0$ inside a superconductor,

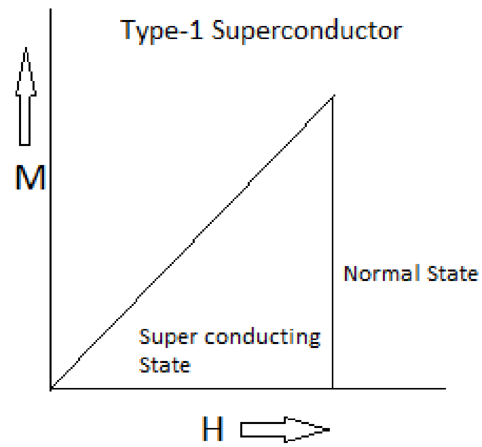
$$(\vec{H} + \vec{M}) = 0$$

$$\Rightarrow \vec{H} = -\vec{M}$$

But, $\chi_M = \mu_r - 1 = \dfrac{\vec{M}}{\vec{H}} = -1, \quad \Rightarrow \mu_r = 0$ Hence, a superconductor is perfect diamagnetic.

Type – I superconductors:

Superconductors which can exhibit complete Missenr effect or perfect diamagnetism are called type-I superconductors. In such case when type –I superconductor is placed in a varying magnetic field H < H_C and on increasing magnetic field the specimen suddenly changes to normal state at H = H_C. i.e. above the critical field (H>H_C) the specimen is in normal state and below the critical field (H<H_C) the specimen in superconducting sate. Type-I superconductors are also known as soft superconductors.

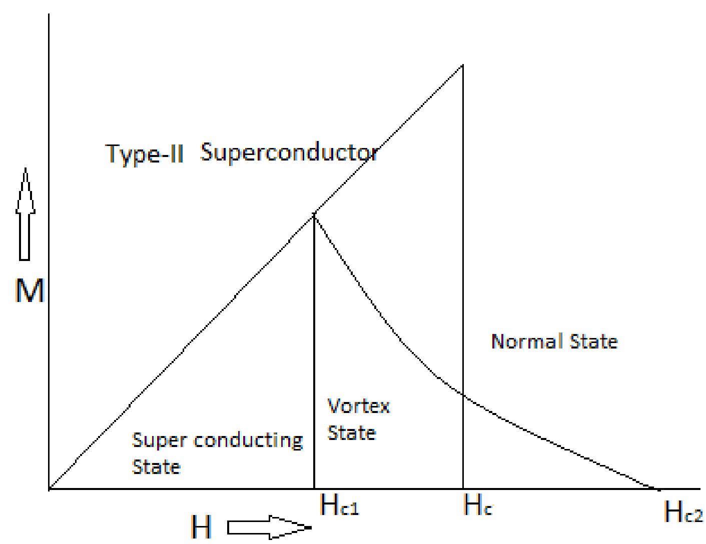


E.g. Zn, Hg, Sn, Ga etc.

Type – II superconductors:

For these superconductors there are two critical fields H_{C1} & H_{C2} when H < H_{C1} the specimen is in superconducting state. When H_{C1} < H < H_{C2} the specimen is in a mixed state i.e. it has both superconducting and normal conducting properties. When H > H_{C2} the specimen lost superconducting properties completely and it is in normal state.

Superconductors which exhibit above phenomenon are called type – II superconductors. Here H_{C1} < H < H_{C2}. These are also called as hard superconductors. These are most useful in commercial purpose.



Comparison between Type-I and Type II Superconductor

Type-I superconductor	Type-II superconductor
1. They exhibit complete meissner effect.	1. They do not exhibit complete meissner effect.
2. They show perfectly diamagnetic behavior.	2. They do not show perfectly diamagnetic behavior.
3. They have only one critical magnetic field Hc.	3. They have two critical magnetic field, lower critical magnetic field H_{C1} and upper critical magnetic field H_{C2}.
4. There is no mixed state or intermediate state in case of these materials.	4. Mixed state or intermediate state is present.
5. The material loses magnetization abruptly	5. The material loses magnetization gradually.
6. Hiest value of Hc is about 0.1 $Wb/m^{2.}$	6. Upper critical field is of the order of 30Wb/m2.
7. They are known as soft superconductors, Example- Lead, tin, Mrcury etc	7. They are known as hard super conductors Example- Nb-Sn, Nb-Ti, Nb-Zr etc

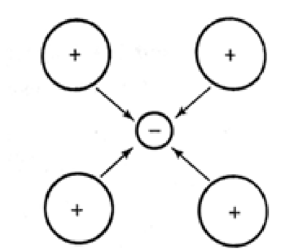
B C S Theory:

This theory is developed by Bardeen, Cooper and Schrieffer. They explained the superconductivity and its properties successfully which involves electron – electron interaction via lattice deformation.

According to BCS theory superconductivity is due to the domination of attractive interaction between two electrons by means of phonon exchange over usual repulsive interaction.

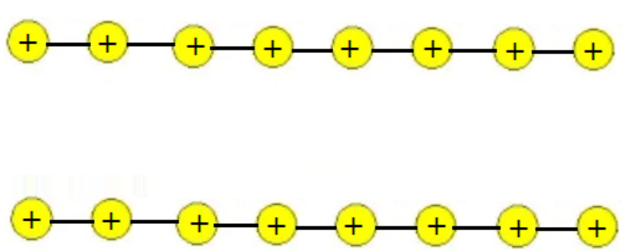
Electron – electron interaction:

Let us consider an electron approaching the lattice of positive ions. Positive ions attract towards the electron and form a positive ion core. Due to the attraction between the charge and the positive ion core the lattice is deformed.

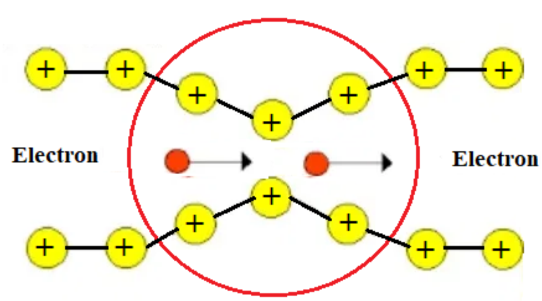


Positive ions attracted towards an electron

The electron is screened by the positive ion core by which the charge of the electron reduces. Suppose another electron approaches the assembly of the electron and the ion core, it is attracted towards the assembly and interacts with the first electron via lattice deformation.



Positively charged lattice ion core



Lattice deformation due to attraction

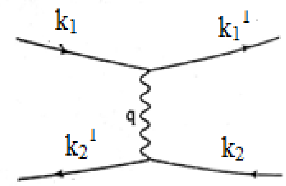
This interaction is due to exchange of virtual phonon 'q' between two electrons. In terms of wave vector the interaction may be expressed as

$$k_1 - q = k_1' \quad \text{And} \quad k_2 + q = k_2'$$

$$\Rightarrow k_1 + k_2 = k_1' + k_2'$$

i.e. the net wave vector is conserved.

The pair of electrons called 'Cooper pair' and the electrons are known as 'Cooper electrons'.



The exchange of virtual phonons between the two electrons (Cooper pair)

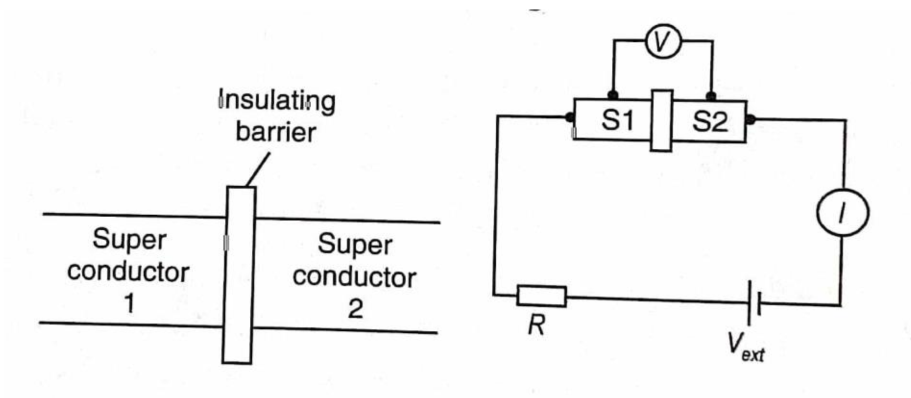
According to Fermi Dirac distribution

$$F(E) = \frac{1}{1 + \exp((E - E_F)/KT)}$$

At T = 0^oK and E < E_F all the energy states below the Fermi level are filled and all the energy states above the Fermi level are empty. So due to the addition of cooper electron they are forced to occupy the energy states above the Fermi level. Due to attraction between the electrons they form a bounded state whose total energy is less than the energy of the pair in the Free State i.e. less than $2E_F$. The difference in the two energy states is the binding energy of the cooper pair. To break cooper pair in to two separate electrons the energy equivalent to binding energy of the cooper pair should be supplied. The binding energy is generally of order 10^{-3}eV.The binding energy of cooper pair is strongest when the electrons forming the pair have opposite moment and opposite spins i.e. $k\uparrow, k\downarrow$. The cooper electrons are the super electrons which are responsible for the superconductivity.

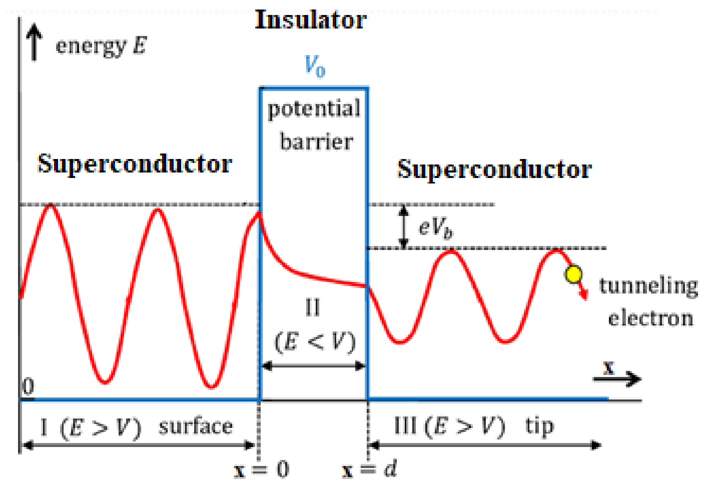
Josephson Effect:

The tunneling of cooper pairs between two superconductors separated by a thin insulating layer is known as 'Josephson Effect'. The tunneling current is very less since the two superconductors are weakly coupled to thin insulating layer. Tunneling of cooper pairs take place even in the absence of applied voltage as well as when a voltage is applied to the super conductors.



D.C Josephson Effect:

According to this effect a d c current flows across the junction of two superconductors separated by a thin insulating layer in the absence of any external electric or magnetic field. The tunneling current is



$$I = I_0 \sin(\phi_0),$$

I_0 is the maximum current flow through the junction. It depends up on the thickness of the junction and temperature. Φ_0 is the phase difference between the two parts of the junction. The magnitude of the current varies from $+I_0$ to $-I_0$

A.C Josephson Effect:

According to this effect when a d c voltage is applied across the junction of the two superconductors separated by a thin insulating layer, R.F current oscillations are generated across the junction.

The expression for R.F current is given by

$$I = I_0 \sin(\varphi_0 + \omega t) = I_0 \sin(\varphi_0 + \Delta\varphi)$$

Now from quantum mechanics $\dfrac{d\phi}{dt} = \dfrac{2eV}{\hbar}$ Where $\hbar = \dfrac{h}{2\pi}$

So $\phi = \int \frac{2eV}{\hbar} dt = \frac{2eV}{\hbar} t + C$

Where C is the constant of integration. When t = 0 then φ = φ_0 so C = φ_0

Hence φ = $\phi = \int \frac{2eV}{\hbar} dt = \frac{2eV}{\hbar} t + \phi_0$

Hence the R.F current is

$$I \Rightarrow \phi = \int \frac{2eV}{\hbar} dt = \frac{2eV}{\hbar} t + C = I_0 \sin \phi = I_0 \sin\left(\frac{2eVt}{\hbar} + \phi_0\right) = I_0 \sin(\phi_0 + \Delta\phi)$$

Where $\Delta\varphi = \left(\frac{2eVt}{\hbar}\right)$

So I = $I_0 \sin\left[\varphi_0 + \left(\frac{2eVt}{\hbar}\right)\right] = I_0 \sin\left[\varphi_0 + 2\pi \frac{2eVt}{h}\right]$

So $\omega t = 2\pi \frac{2eVt}{h} \quad \Rightarrow \quad \omega = 2\pi \frac{2eV}{h} = 2\pi f$

The current represents an alternating current with frequency $f = \frac{2eV}{h}$

Applications of Josephson Effect:

1. It is used to generate microwave of frequency $f = \frac{2eV}{h}$
2. It is used to define standard volt by national Bureau of Standards.
3. It is used to measure very low temperature. For this A C Josephson effect is used.
4. It is used as a switching device with a switching time of 1 Pico second.

High T_C Superconductors

Based on transition temperature superconductors are divided into two categories as low $\mathbf{T_C}$ and high $\mathbf{T_C}$ superconductors. The materials having $\mathbf{T_C}$ below 24K are regarded as low $\mathbf{T_C}$ superconductors and those having $\mathbf{T_C}$ above 27K are regarded as high $\mathbf{T_C}$ superconductors.

Examples

1. **LBCO-** Mixed metallic oxide of lanthanum-barium-copper ($La_1Ba_2Cu_3O_7$) exhibited super conductivity at about 30K.

2. **YBCO-**Mixed metallic oxide of Yittrium-barium-copper ($Y_1Ba_2Cu_3O_7$) exhibited super conductivity at about 95K.
3. **BSCCO-** Mixed metallic oxide of Bismuth, strontium, calcium and copper ($Bi_2CaSr_2Cu_2O_{10+x}$) exhibited super conductivity at about 110K.

The oxygen vacancies are found to play a key role in the superconducting behavior of ceramic oxide. When the cell contains one atom of rare earth metal, two barium atoms, three copper atoms have seven oxygen atoms then such compounds are called 1-2-3 superconductors.

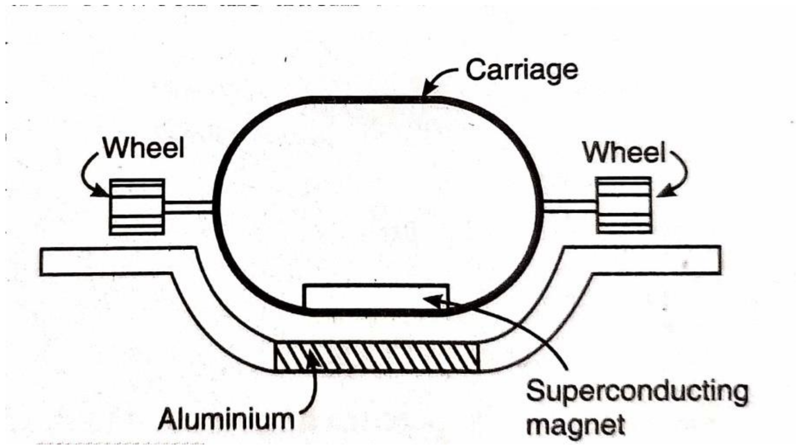
Properties of High T_C Superconductors

1. High T_C Superconductors are brittle in nature.
2. The properties of the normal state of these materials are highly anisotropic.
3. The Hall coefficient is positive indicating that the charge carriers are holes.
4. Their behavior can not be explained by BCS theory.
5. The isotope effect is almost absent in these materials.
6. The magnetic properties of these materials are highly anisotropic.

Applications of superconductors:

1. **Transformers and electrical Machines:** The transformers and electrical machines with superconducting coils generate stronger magnetic field hence the size of the motors and generators will be drastically reduced. In this case the eddy current loss is very less therefore they are having 99% efficiency.

2. **Magnetic levitation: (MagLev Trains)**
   Since superconductors are diamagnetic substances and magnetic field inside them is zero, therefore hey can be suspended in air against the repulsive force from a permanent magnet. This effect is known as 'magnetic levitation'.
   The basic idea of this is to levitate it with magnetic fields so that there is no physical contact between the trains and the guide ways. Consequently the MagLev train can travel at high speed.
   Principle
   Maglev trains work on the principle of magnetic repulsion between the cars and the track.



Operation-

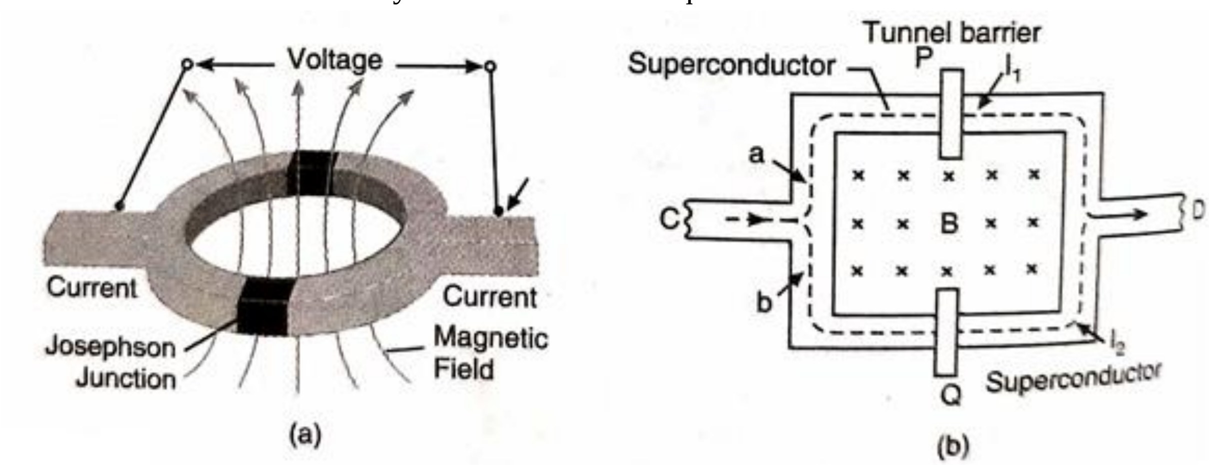
In case of MagLev train, the train has superconducting magnets built into the base of its carriages. An aluminium guide-way is laid on the ground and carries electric current. The repulsion between the two powerful magnetic fields, namely the field produced by the super conductor magnet and the field produced by the electric current in the aluminum guide-way causes magnetic levitation of the train. A levitation of about 10 to 15cm is achieved so that the train floats in air.

3. **SQUIDS** (Super conducting quantum interference devices)- SQUID is a device used to measure extremely weak magnetic flux.

There are two main types of SQUIDS. DC SQUID AND AC SQUID.

Fabrication.

SQUIDS are fabricated by depositing a thin niobium layer on an alloy having 10% gold or indium. It act as the basic electrode of the SQUID and the tunnel barrier is oxidized onto this niobium surface. The top electrode is a layer of lead alloy deposited on top of the other two. The entire device is cooled to nearly absolute zero with liquid helium.

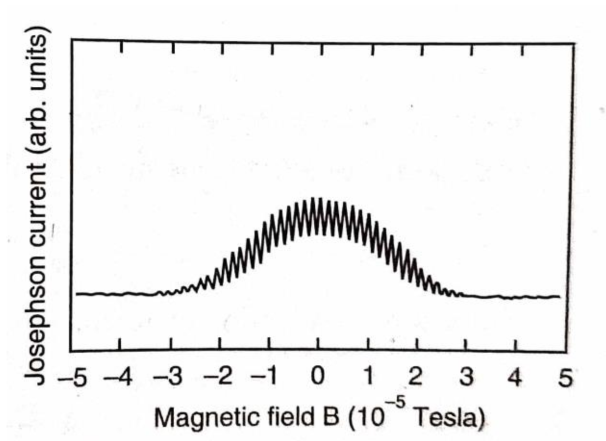


A two junction DC SQUID consists of two Josephosons arranged in parallel so that electron tunneling through the junctions demonstrate the quantum interference.

Working

As DC super current is applied to the SQUID which is the bias current, it enters the device through the arm C. It is divided along two paths a and b and again merge into one and leaves through the arm D. P and Q are the Josephson junctions and. I_1 and I_2 are the currents tunneling through the junction P and Q respectively.

When a magnetic field is applied perpendicular to the loop, the flux passes through the loop changes the quantum mechanical phase difference across each of the two junctions. Then the wave functions at the two Josephson junctions interferer with each other.



Then the total current through two parallel Josephson junction is

$$I_T = 2(I_0 \sin \delta_0) \cos \frac{2\pi e\Phi}{hC}$$

The above relation indicates that a progressive increase or decrease of magnetic flux, causes the current to oscillate between a maximum and a minimum value. The period of the oscillation is one flux quantum $\Phi_0 = \frac{h}{2e}$ = 2.06 x 10^{-15} Weber

Uses of SQUID.

1. SQUIDS are used to study tiny magnetic signals from the brain and heart.
2. SQUID magneto meters are used to detect the paramagnetic response in the liver. This gives the information about the amount of iron held in the lever of the body accurately