Module: super conductivity

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• Introduction

it was observed by kumerlingh onnes in 1911, while he was observing resistivity of Hg at lower temp. The resistivity of Hg became 0 at 4.2 k.

" Superconductivity means the electrical resistance of a material suddenly drops to zero when it is cooled below a certain temp. called critical temperature. This property is known as Super conductivity "

The temp at which a normal metal is converted into a superconductor and vice versa is known as critical temp. (transition temp) T_c.

• Properties of superconductors

Superconductors are having different properties. few of them are given below.

① Effect of magnetic field.

When large magnetic field is applied to a superconductor, the superconductivity is destroyed of the material. The minimum field required to destroy the superconductivity is known as critical ~~mag~~.mag. field (H_c)

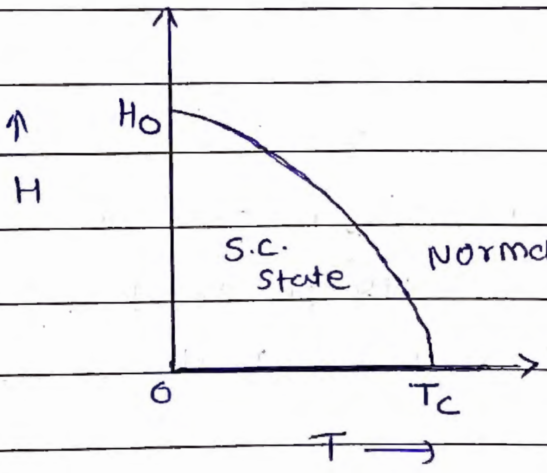
$$\therefore \quad H_c = H_0 \left[1 - \left(\frac{T}{T_c} \right)^2 \right]$$

where H_c = critical mag. field

H_0 = critical mag. field at $T = 0^\circ K$

T = Temp.

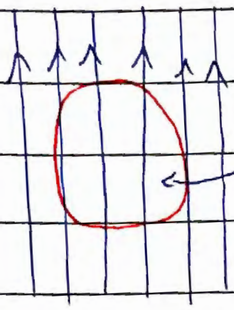
T_c = critical temp.



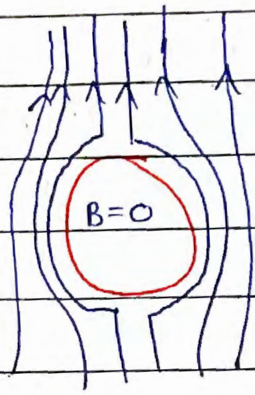
→ The variation of H_c is shown in the figure. The material is superconductor inside the curve and Non S.C. outside the curve.

② Meissner effect.

The complete expulsion (divergence) of all the magnetic field by a superconducting material is known as Meissner effect.



$T > T_c$ and $H > H_c$



$T < T_c$ $H < H_c$

When a superconducting material is placed in a magnetic field ($H > H_c$) at room temperature, all the mag. flux is pass through (penetrate) that material.

But when a superconductor is placed in a magnetic field (~~H>Hc~~) and temp less than T_c ($T < T_c$) then the mag. flux is diverge from the material. (means its not pass through material).

The above process is because of development of surface current. and because of that magnetization M within the superconducting material. The magnetization (M) and applied field are equal in magnitude and opposite in direction. So they cancell each other inside the material. Thus, superconductors are perfectly diamagnetic materials ($\chi_m = -1$).

$$B = \mu_0 (M + H)$$

where: B = mag. induction

μ_0 = permeability of free space

M = magnetization

H = applied mag. field.

Now $B=0$ inside the material (SC)

$$\therefore \mu_0(M+H)=0$$

$$\mu_0 \neq 0$$

$$\therefore (M+H)=0$$

$$M=-H$$

$$\therefore \frac{M}{H}=-1$$

$\therefore \frac{M}{H}$ is also known as $\chi_m =$ susceptibility

$$\therefore \chi_m=-1$$

So $\chi_m=-ve$ and if $\chi_m=-ve$ then the materials are diamagnetic. So superconducters are diamagnetic.

③ Pressure effect.

Few material shows superconductivity on increasing pressure over them.

For example cesium is normal conductor at normal atmospheric pressure, but if at $T_c = 1.5K$ we apply pressure of 110 kbar. then cesium will convert into a superconductor.

④ impurity effect.

When impurities are added to a superconductor the superconducting property is Not lost but their T_c value is lowered

This is known as impurity effect.

⑤ Isotopic mass effect.

Maxwell found that T_c is inversely proportional to the square root of Atomic weights of S.C.

this is known as isotope effect.

mathematically it is expressed

$$T_c \propto \frac{1}{\sqrt{M}}$$

$$\therefore \sqrt{M} \cdot T_c = \text{a constant.}$$

The T_c value of a superconductor is changes with change in isotopic mass. the variation in T_c with isotopic mass (M) is known as isotopic effect.

- **Mechanism of superconductivity : BCS theory.**

in 1957 Bardeen , cooper and schrieffer proposed a microscopic theory known as BCS theory. The theory explains the phenomena associated with superconductivity. it involves electron interaction through phonons as mediators.

superconductivity occuring at low temp. because the resistence decreases. which is given by damping of the interior magnetic field (Meissner effect) and the complete absense of electrical resistence.

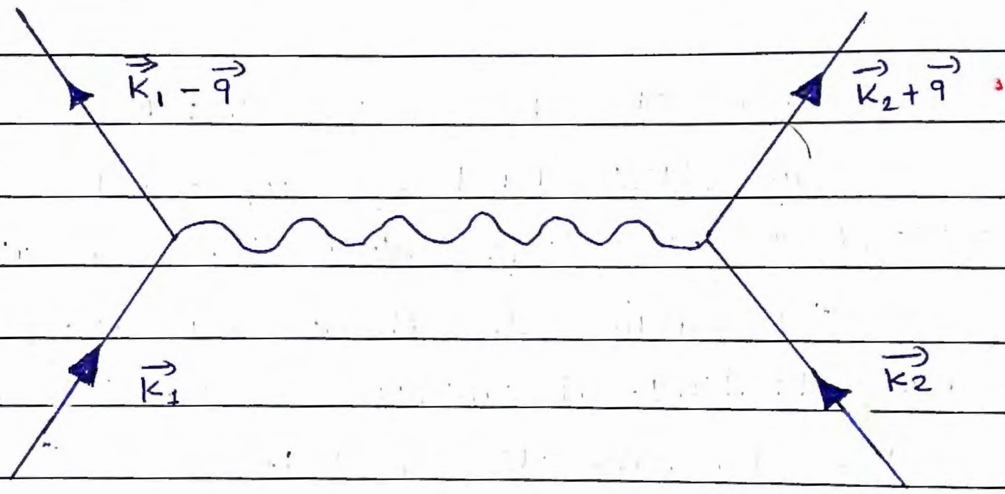
In conventional superconductors superconductivity is happen because certain conduction electrons arising from exchange of phonons.

According to BCS theory superconductivity is due to attractive interaction between electrons at very low temperature. Due to attractive interaction electron start moving in pair called cooper pair.

The two electrons in the cooper pair move coherently through lattice in such a way that they do not suffer any collision with lattice ions.

It appears as if two electrons are bonded to each other and behave like a single particle known as cooper pair. The two electrons in cooper pair exchange phonon through lattice ions.

★ Electron - Lattice - Electron interaction :



The main idea behind BCS theory is experimental results of two effects (1) Isotop effect (2) variation of specific heat with temperature.

From isotope effect $T_c\sqrt{M}$ = constant, one can say that the transition resulting in S.C. state must involve the dynamic of ion motions, lattice-vibrations, or phonons.

It is assumed from BCS theory that the electron - phonon interaction produce an attractive interaction between two electrons.

For example an electron of wave vector k_1 emits a virtual phonon which is absorbed by an an electron k_2. Thus k is scattered as $k_1 - q$ and $k_2 + q$ as shown in figure. The resulting electron electron interaction depends on relative magnitude of the electronic energy change and phonon energy. once the Phonon energy exceeds the electronic energy the interaction becomes attractive interaction

Thus for attractive interaction the wave vector and spin are represented as $\vec{k_1}$ and $\vec{k_2}$. Therefore, the two electrons interacting attractively in the Phonon Field are called cooper Pair and the same is shown in figure.

★ coherence length:

The Paired electron (cooper pair) are not scattered because of ~~their~~ they smoothely ride over lattice point. the Cooper Pairs are not Slowed down hence the substance does not Posses any electrical resistivity.

Superconductivity is due to the mutual interaction and correlation of elecrons over a considerable distance called coherence length (ξ_0)

The maximum distance up to which the states of pair electrons are correlated to produce superconductivity is known as coherence length (ξ_0)

generally $\xi_0 = 10^{-6}$ m.

The ratio of London penetration depth (λ) to the coherence length (ξ_0) is given by K

$$K = \frac{\lambda}{\xi_0} \quad \text{is a number.}$$

For type-I S.C. $K < \frac{1}{\sqrt{2}}$

for type-II S.C. $K > \frac{1}{\sqrt{2}}$

- Penetration depth (London eqn) : Magnetic Field.

In 1935 F. London and H. London obtain the london eqn. for penetration depth.

According to them the applied mag. Field does not drop to zero at the surface of the superconductor but decreases exponentially as given by the equation.

$$H = H_0 \exp\left(\frac{-x}{\lambda}\right)$$

where H = intensity of mag. Field at depth x from surface

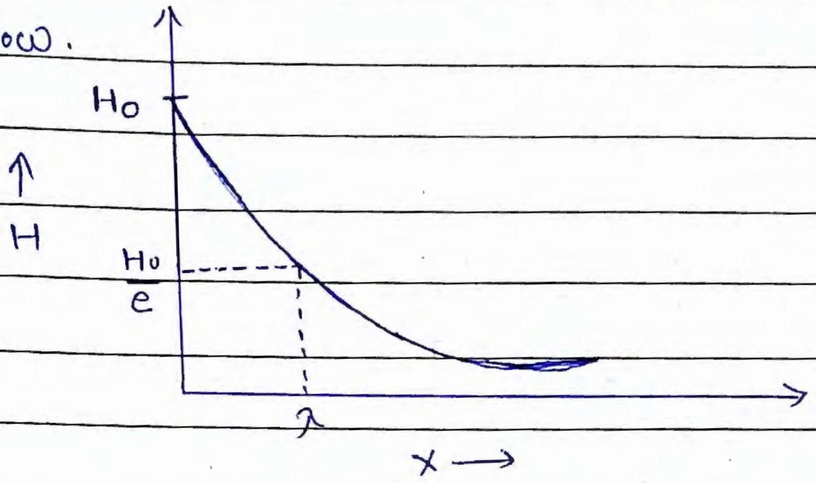
~~H_0~~

H_0 = Intensity of mag. Field at surface

λ = London penetration depth

" London penetration depth (λ) is defined as the distance from the surface of the superconductor to a point inside the material at which the intensity of mag. Field is ($1/e$) of the mag. Field at surface (i.e H_0/e)

The variation of intensity of mag. field with distance from the surface into the material for tin is shown below.



The mag. field is likely to penetrate to a depth of 10 to 100 nm from the surface of a superconductor. If the superconductor film or filament is thinner than this value then its properties are different from that bulk material.

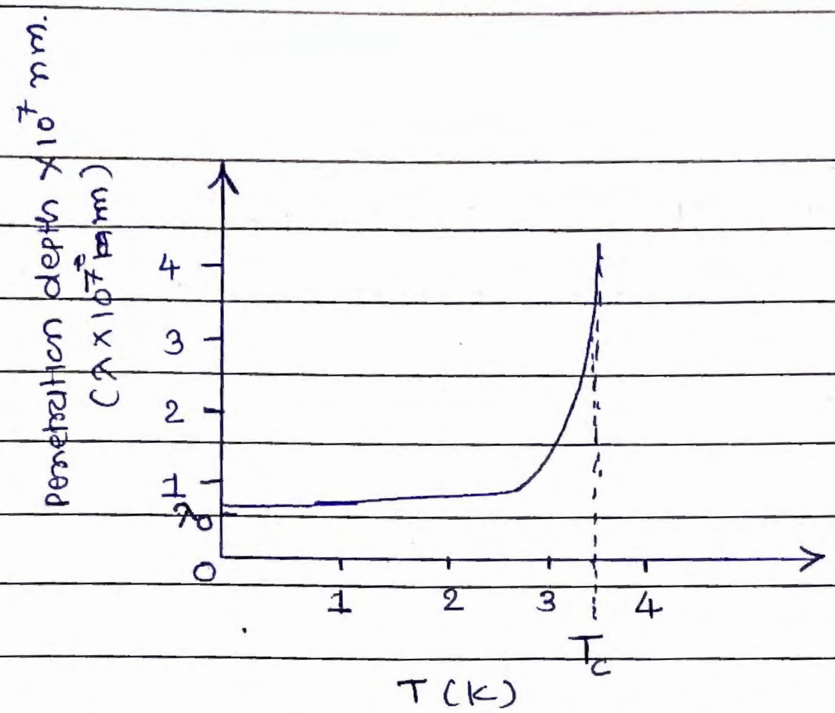
The penetration depth (λ) is not constant but varies with temp as shown is figure.

From the figure we can say tha (λ) is independent of temp. but (λ) increases rapidly and approaches infinity as the temp approaches the transition temp of the material.

The λ at temp $T(<T_c)$ can be obtained using the equ.

$$\lambda = \frac{\lambda_0}{\left[1 - \left(\frac{T}{T_c}\right)^4\right]^{1/2}}$$

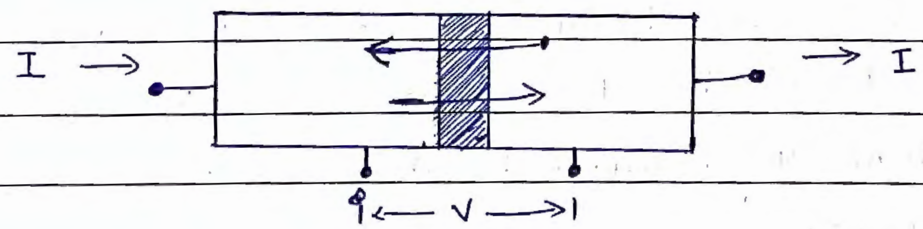
where λ_0 is the London penetration depth at 0K



variation in penetration depth in tin

- **Josephson Junction and its application.**

Two superconductors are separated by a very thin layer of an insulator forms a Josephson junction.



The wave nature of moving particle makes the electrons to tunnel through the barrier (insulator) The electron can tunnel from one superconductor to the other. As a result the tunneling of electrons (cooper 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.

(i)

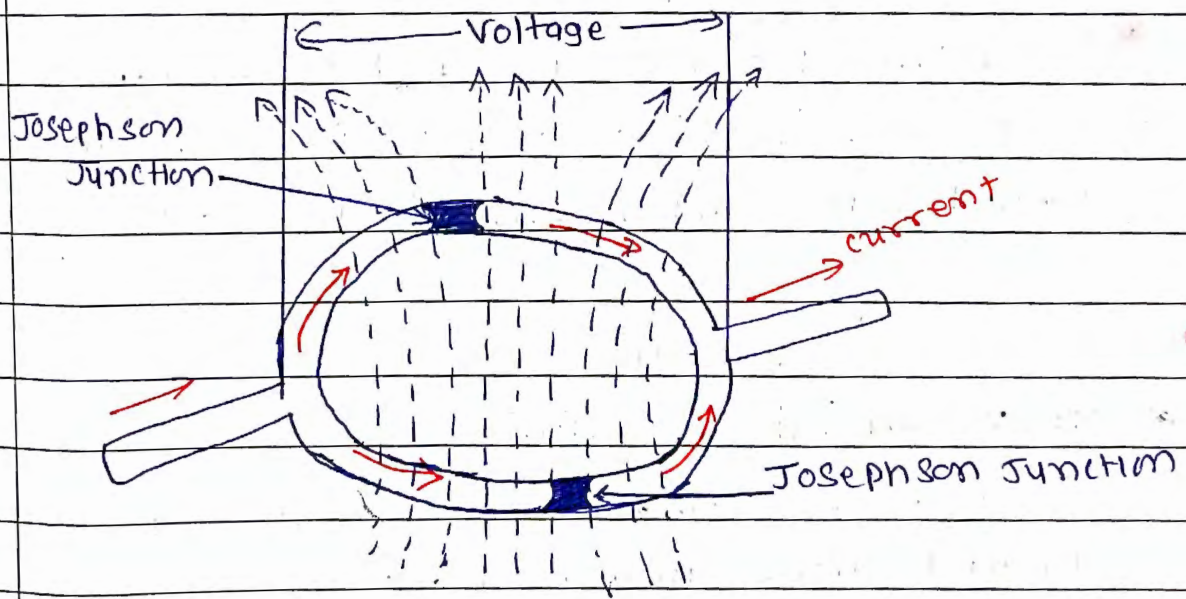
(ii) ... connecting two Josephson ... parallel

The magnitude of current depends on the thickness of the insulator, the nature of the material and the temperature.

on the other hand, when a potential difference V is applied between two sides of the junction there will be an oscillation of the tunneling current with angular frequency $v = \frac{2eV}{h}$. This is called a.c. Josephson effect.

Thus according to a.c. Josephson effect the junction generates an a.c current at a freq. of $\frac{2eV}{h}$ Hz per volt.

★ Application of josephson junction.



Josephson Junction are used in sensitive magnetometers called SQUID (superconducting quantum interference device)

SQUID is formed by connecting two Josephson Junction Parallel

When current is passed into the arrangement it splits flowing across the two opposite arc. The current through the circuits 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} V.

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

weak magnetic field produced by biological current such as those in brain can also be detected using SQUIDs.

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

• Applications of Superconductors.

★ Maglev (magnetic Levitation)

it is the phenomenon in which an object is suspended above another object with no other support but no magnetic fields.

we know that perfect diamagnetic substance repels a magnetic field. Superconductors are perfect diamagnetic they are useful in motors and bearings.

It is on the basis of meissner effect.

- in maglev there is absence of contact between moving and stationary systems, the friction is eliminated. With such arrangement great speed can be achieved with low energy consumption.

The maglev is based on (1) Ele.mag. suspension (EMS) and (2) Electrodynamic suspension (EDS)

In EMS the electromagnets installed on the train bogies attract the iron rails (guidways) The vehicle magnets wrap around the iron wrap the guidways upward force lift the train.

in EDS levitation is achieved by creating repulsive force between the train and guideways.

★ Josephson Effect and its application.

Answer is given in the previous point.

★ SQUID - superconducting quantum interference device.

which is useful to detect very small current or magnetic flux.

★ Superconductors can be used to transmit electrical power over very long distance without any power loss or any voltage drop.

★ superconducting generators has the benefits of small size and low energy consumption than the conventional generators

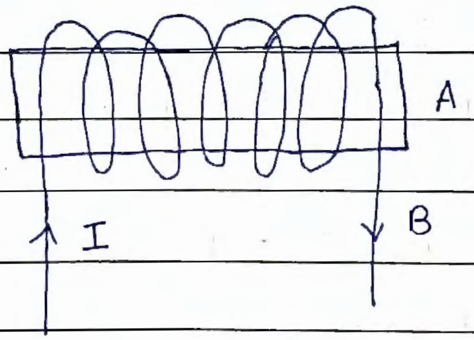
★ superconducting coils are used in NMR (nuclear magnetic resonance) imaging equipment which are used in hospital fo scanning of whole body to diagnose medical problems.

* very strong magnetic field can be generated with coils made of high Tc superconductor materials.

* Superconducters can act as relay or switching systems in a computer They can also be used as memory storage elements in computer.

Cryotron : it is a relay or switch made of superconductors whose size can be made very small. and they consume very less current.

it consist of two superconducting material A and B . Let the material A be inside the coil of wire B.



Let the critical field of material A be H_{cA} and that of B. be H_{cB} respectively. and $H_{cA} < H_{cB}$

if current I is passed through the material B , the current induces magnetic field H. If $H > H_{cA}$ then the superconducting property of material A is destroyed.

So the resistivity increases and the contact is broken . Thus the current A can be controlled by the current in B . So the system act as relay or switch

* very fast and accurate computers can be constructed using superconductors and the power consumption is also very low.
* ore separation can be done efficiently using superconducting magnets.