Superconductivity

An Introductory study of superconductor for B-tech and B.Sc. 1st year students.
It can help the students to understand superconductivity in a very short time.

SUPERCONDUCTORS

- Superconductivity is a phenomenon in certain materials at extremely low temperatures, characterized by *exactly zero electrical resistance* and *exclusion of the interior magnetic field* (i.e. the **Meissner effect)**

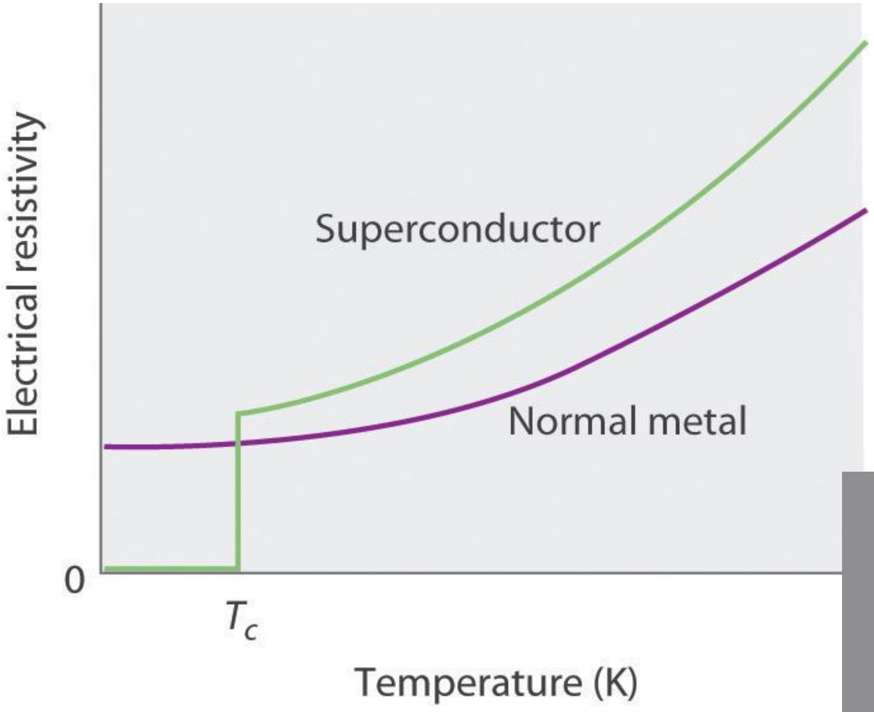
Examples: Lead, niobium nitride

Conductor has some resistance at 0K but the **Superconductor** has zero resistance at 0K

Superconductivity is something which is more than conductivity. Electrons are responsible for current to flow. These electrons experience collision with lattice phonon which creates resistance.

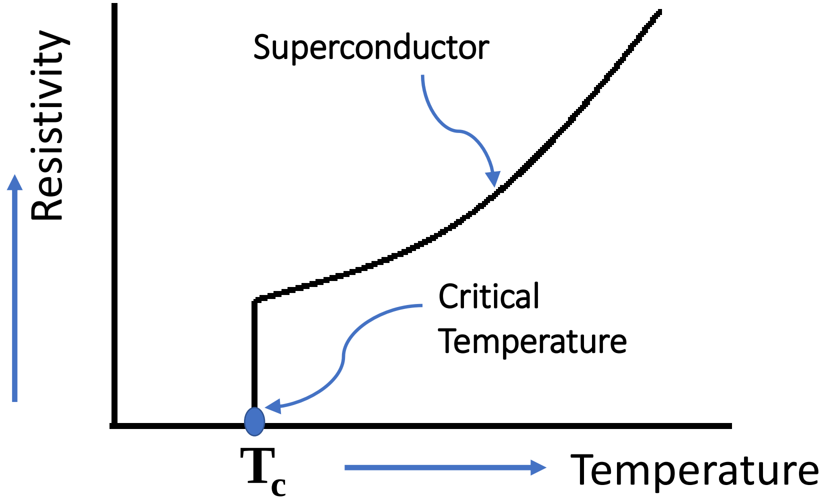
FOUNDER

1. Superconductivity was discovered in **1911** by ***Heike Kamerlingh Onnes***
2. At the temperature of **4.2K**(***Critical Temperature***), he observed that the resistance abruptly disappears in case of mercury.
3. For this discovery he got the NOBEL PRIZE in PHYSICS in 1913.



Critical Temperature

- *It is the Temperature above which the superconductor becomes normal metals. It is denoted as* T_c.
- *Thus below* T_c *it shows superconductor nature. Above* T_c *superconductor becomes normal metals.*



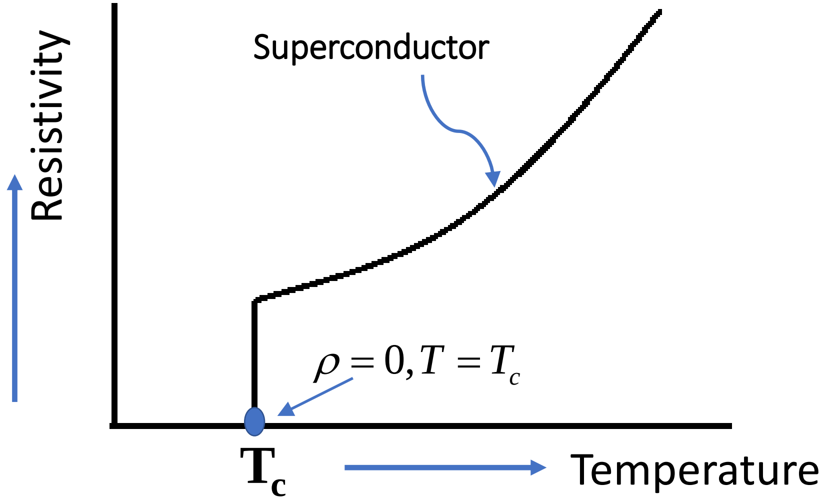
Temperature Vs Resistivity curve for a superconductor

Two main Characteristic feature of superconductor

1. **Zero electrical resistance**
2. **Meisner effect**

Zero electrical resistance

- Zero electrical resistance = infinite conductivity.
- Electrons flow without facing any resistance. That’s why no heat is generated within the material.
- $\rho = 0$; ρ is called the resistivity.
- $\sigma = \infty$; σ is called the conductivity.



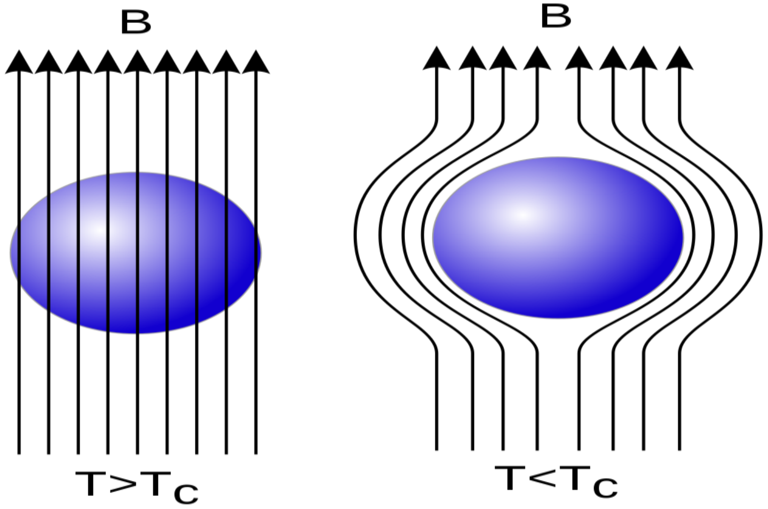
Temperature Vs Resistivity curve for a superconductor

Meissner effect

- When the superconductor is cooled below its critical or transition temperature(Tc) all the magnetic flux are repelled by the superconductor . That means they show perfect diamagnetism. i.e. *B = 0 inside the superconductor*. This Phenomena is called the Meissner Effect.

For Perfect diamagnet *magnetic*

- *Susceptibility*= $\chi_m = M/H = -1$



Repulsion of magnetic field below transition temperature Tc

Other Properties of Superconductor

1. Effect of magnetic field(Critical Magnetic Field).
2. Effect of impurity.(Isotope effect)
3. Flux Quantization.
4. Entropy and Coherence.
5. Specific Heat.
6. Josephson Effect.

Effect of Magnetic Field(Critical Magnetic Field)

The magnetic field above which superconductivity disappears and the superconductor becomes normal metal is called the critical magnetic field **H_c**

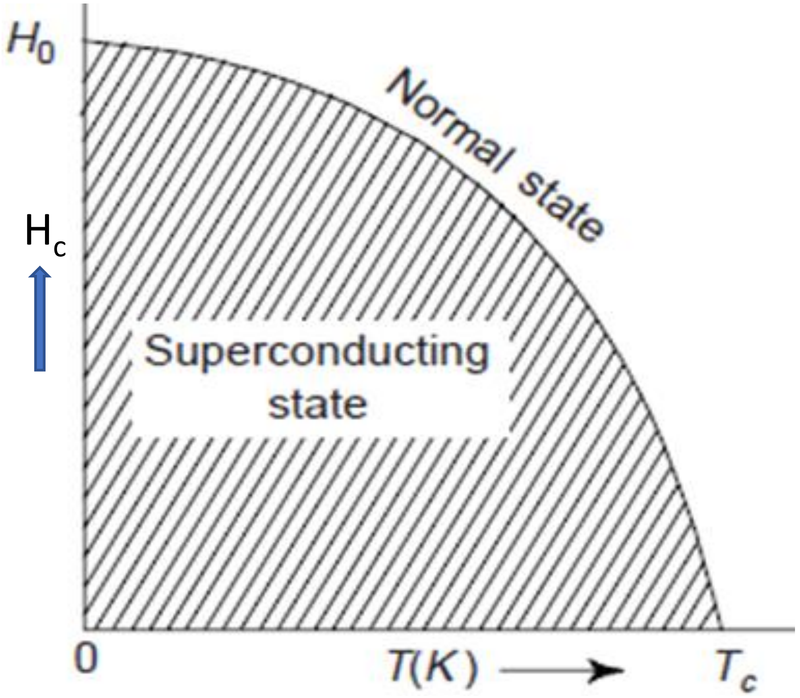
Critical magnetic field (H_C) depends on the temperature as follows

$$H_C = H_0\left[1-\left(\frac{T}{T_C}\right)^2\right]$$

H_0 – Critical field at 0K

T - Temperature below T_C

T_C - Transition Temperature



Variations of Critical Magnetic field with Temperature

Isotope Effect

- *According to Reynolds, The Transition temperature of a superconductor material is proportional to* $M^{-1/2}$ *, where M is the isotopic mass.*
- *That is* $\boxed{T_c M^{1/2} = con.}$

Flux Quantization

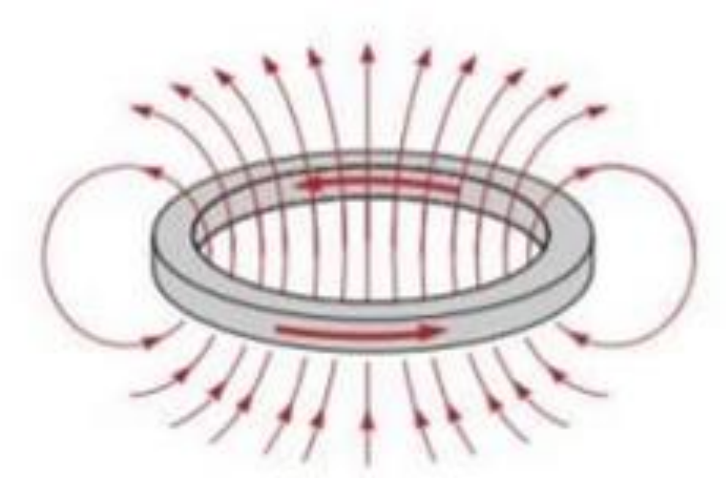
- The magnetic field passing through the superconducting ring is quantized. The quantized flux is given by,

$$\phi = \frac{nh}{2e}$$

The quantity $\phi_0 = \frac{h}{2e}$ **is called the Fluxoid.**

h **is the Plank constant and** e **is the electronic charge**

$$\phi_0 \approx 2.07 \times 10^{-15} weber$$



Magnetic lines of Force Passing through a Superconducting ring

Specific Heat

For normal metal Specific heat is of the form,

$$C_n(T) = AT + BT^3$$

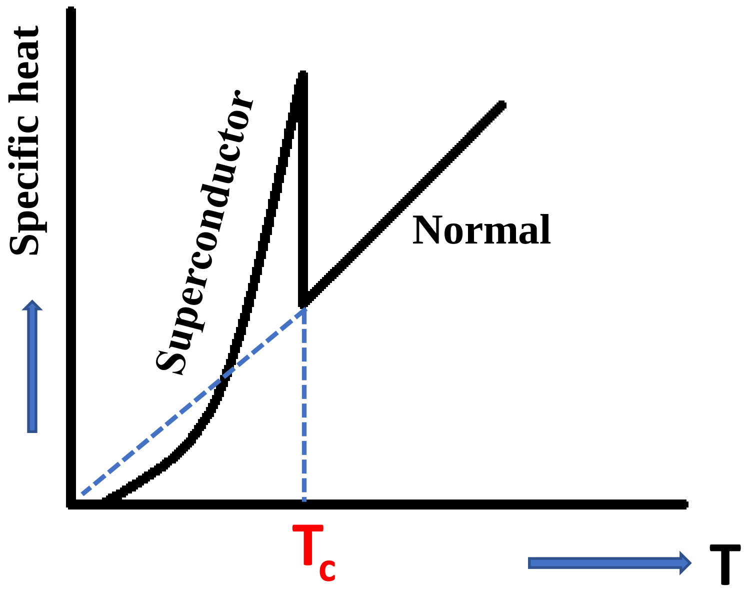
Electronic Part

Lattice Part

For superconductor only the electronic part get modified as,

$C_{es}(T)=\text{constant} \times e^{-\Delta/KT}$

$\Delta = E_g / 2,$ is called energy gap parameter



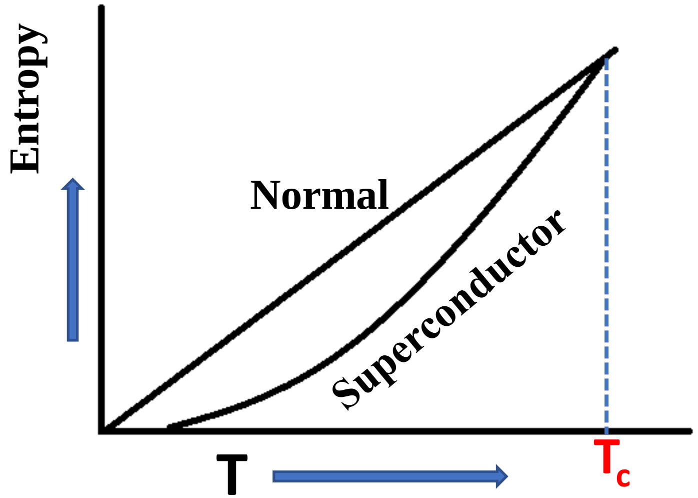
Variation of specific heat with temperate

Entropy And Coherence

Significant decrease in Entropy is observed during normal to superconducting transition

$$Entropy \propto \frac{1}{order}$$

Superconducting state is more ordered than the Normal state



Entropy Vs Temperature(T) for Normal and superconductor

Coherence length

The electronic order may extend up to ***1 micro-meter***.
This range is called the coherence length.

Types of superconductor

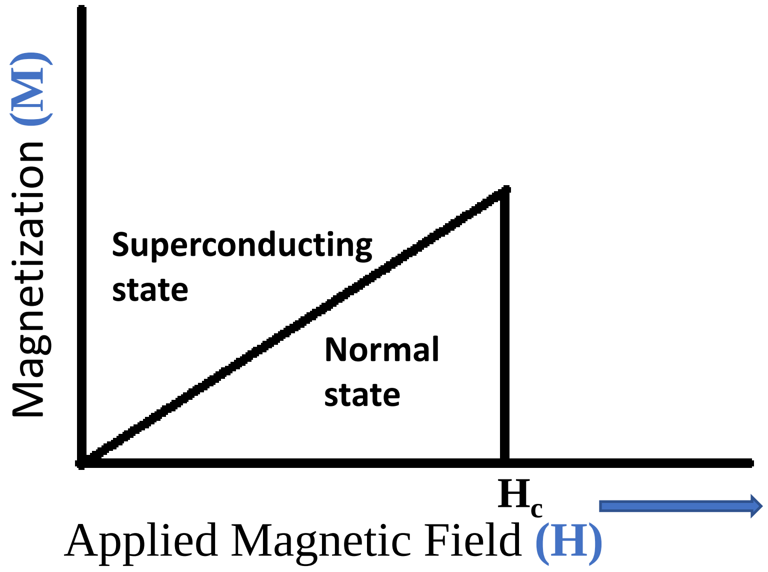
Type1

1. Very low transition temperature. (***Critical temperatures between 0.000325 °K and 7.8 °K***)
2. Sudden loss of magnetization
3. Strictly follow Meissner Effect
4. No mixed state
5. Also called Soft superconductor
6. Examples – Pb, Sn, Hg

Type2

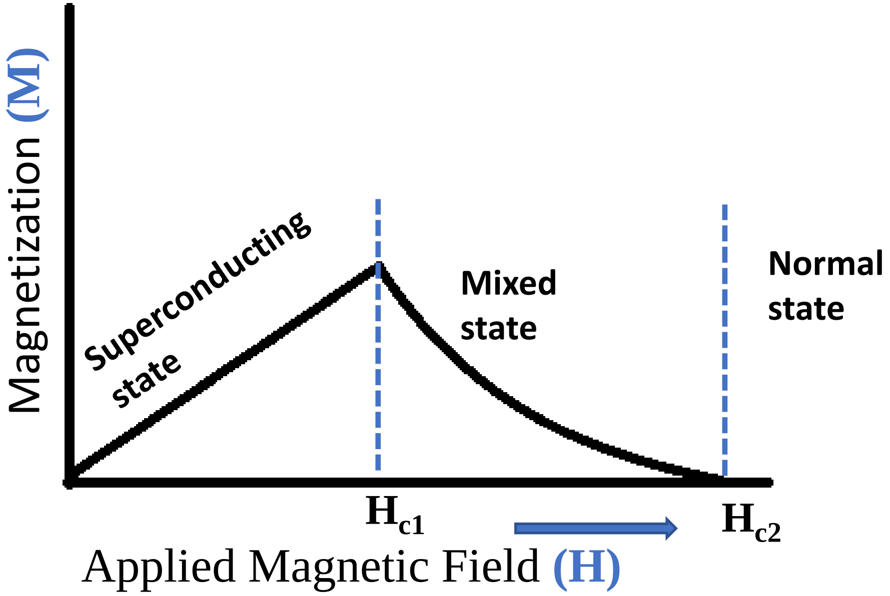
1. High transition temperature compared to type1
2. Gradual loss of magnetization
3. Does not exhibit complete Meissner Effect
4. Mixed state present
5. Also called Hard superconductor.
6. Examples – Nb-Sn, Nb-Ti

M-H curve for Type1 and Type2 Superconductor



Type1

Type1 superconductor has two states. 0 –H_c is the superconducting state and after H_c we have normal state.



Type2

Type2 superconductor has three states. 0 –H_{c1} is the superconducting state H_{c1} to H_{c2} is the Mixed state After H_{c2} we have normal state

Effect of Magnetic Field

(ii) Meissner-Ochsenfeld Effect (B = O inside the superconductor):

The magnetic inductance becomes zero inside the superconductor when it is cooled in a weak external field. The effect is called the Meissner-Ochsenfeld effect.

The superconducting metal always expels the field from its interior, and has $\vec{B} = 0$

The superconducting state of a metal exists 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 critical value.

Josephson Effect

Definition:

The Tunneling of superconducting electrons through a thin insulator placed between two superconductor is known as Josephson effect. The effect is named after the British physicist Brian Josephson in 1962.

Explanations:

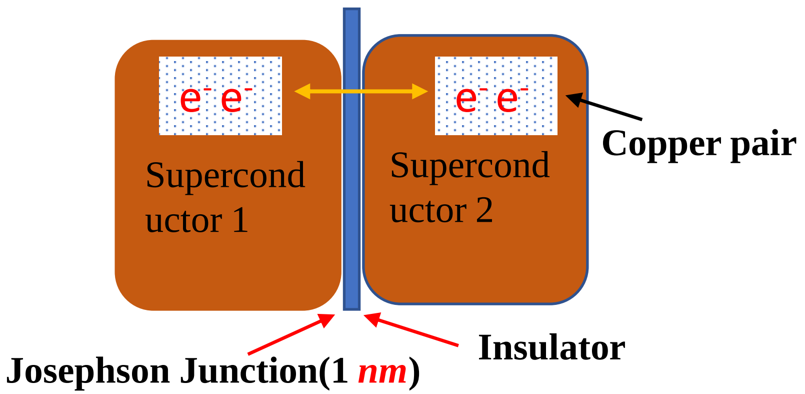
Due to wave nature of electrons. The electrons can tunnel from

One superconductor to another due to its quantum mechanical

Behavior.

There are two types of Josephson effect,

1. **D.C. Josephson Effect.**
2. **A.C. Josephson Effect**



*Flow of electrons(cooper pairs) through a thin insulator placed between two superconductors(**D.C. Josephson effect)***

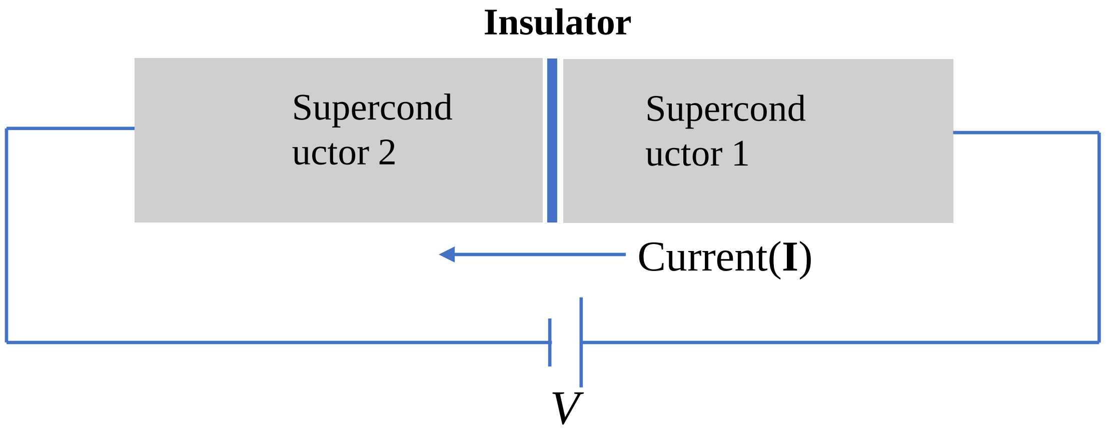
Josephson Effect

D.C. Josephson Effect

- The DC Josephson effect is a direct current crossing the insulator in the absence of any external electromagnetic field.

A.C. Josephson Effect

- When a constant voltage source(V) is applied between the superconductors an high frequency alternating current flows through the superconductor. The frequency of the ac current is, $f = 2eV/h$
- This effect is known as AC Josephson effect.



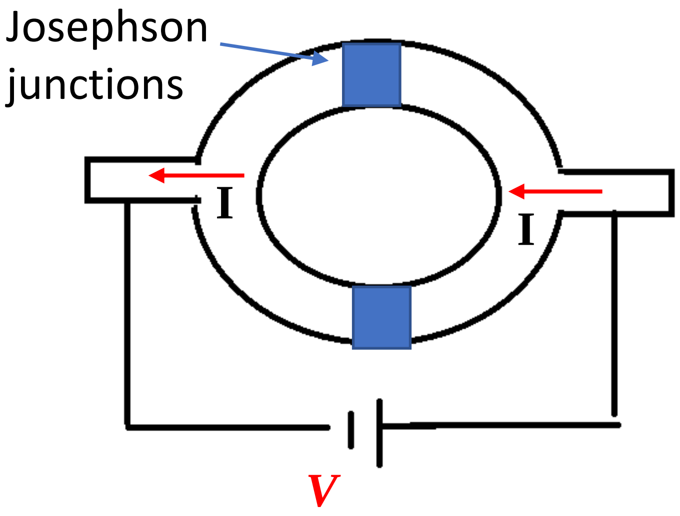
Superconductor quantum interference device(SQUID)

- A **SQUID** is a very sensitive magnetometer used to measure extremely weak magnetic field.
- **Applications**

1. To measure very small magnetic field as low as 5×10^{-18} Tesla.

2. To measure biological current in the human brain

3. To measure Earth magnetic field.



*Schematic diagram of a **SQUID. I** is the current and **V** is the applied voltage*

London’s Equations

- The super-current density, $\mathbf{J_s}$ of a superconductor is described by London Equation.

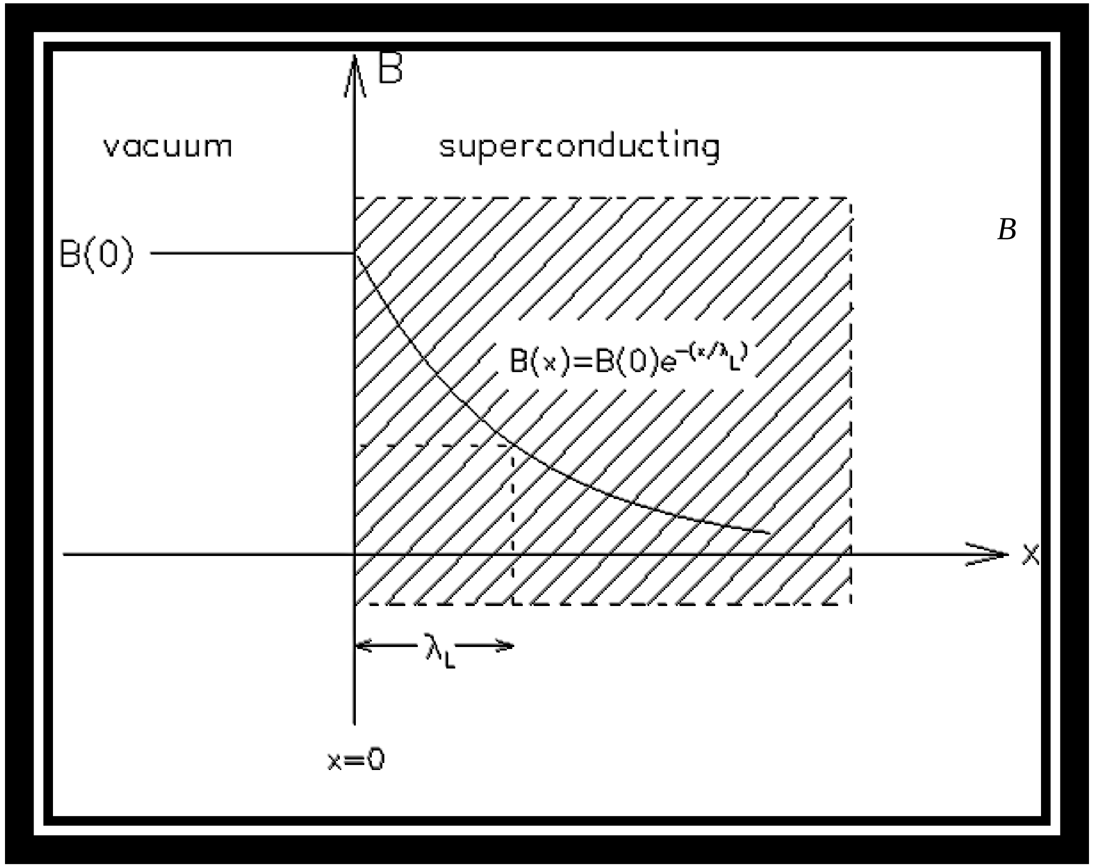
$$\frac{dJ_s}{dt}=\frac{n_s e^2 E}{m}$$

Its differential form is,

$$\nabla \times J_s = -\frac{n_s e^2 B}{m}$$

E=Electric field.
m, e =Electronic mass and charge resp.
$\mathbf{n_s}$=Super electrons density.

Penetration depth



The magnetic field inside a superconductor vary as,

$$B(x) = B(0)e^{-x/\lambda_L}$$

B(x)=Field at a distance x
B(0)=Field at the surface

$\boxed{\lambda_L}$ is the London Penetration depth is given by,

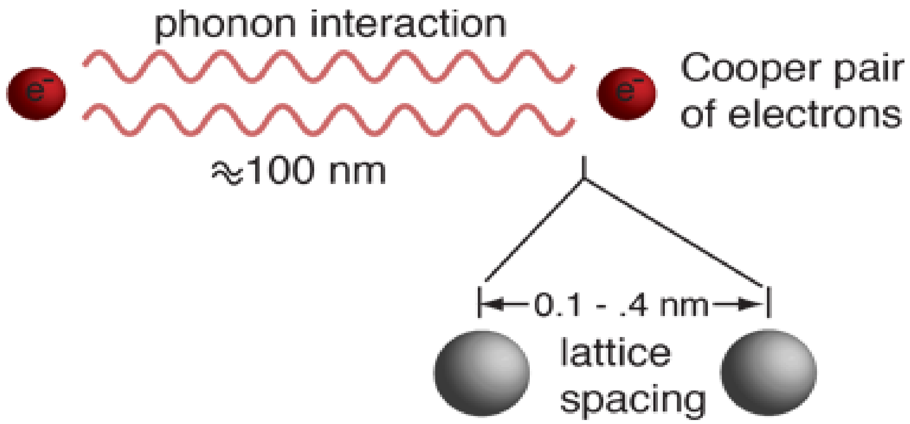
$$\lambda_L = \sqrt{\frac{m}{\mu_0 n e^2}}$$

The distance where the field becomes $1/e$ times of its initial value

$$x = \lambda_L ; B(x) = B(0)/e$$

BCS THEORY

1. The most successful attempt to explain superconductivity is the BCS theory. It was proposed by BARDEEN COOPER AND SHRIFFER in the year 1957.
2. According to this theory superconductivity is due to the attractive force between two electrons mediated by lattice quanta(phonon).
3. These two bounded electron is called the cooper pair. These electron pair does not experience any resistance while travelling through the lattice.



Applications

1.The main application for superconductivity is in producing the large-volume, stable, and high-intensity magnetic fields required for magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR).

2. High temperature superconductor are of limited use.

3. High sensitivity particle detectors.

4. In Maglev (magnetic levitation) trains. These superconductor creates a repulsive magnetic field so that the train will float above a superconductor – this virtually eliminates the friction between the train and the track.

Levitation means an object is suspended by a force against gravity, in a stable position without solid physical contact

A ***high-temperature superconductor levitating above a magnet. Persistent electric current flows on the surface of the superconductor, acting to exclude the magnetic field of the magnet*****(Meisner effect)*****. This current effectively forms an electromagnet that repels the magnet.***

Medical Applications

1) NMR – Nuclear Magnetic Resonance – Scanning
2) Brain wave activity – brain tumor, defective cells
3) Separate damaged cells and healthy cells
4) Superconducting solenoids – magneto hydrodynamic power generation – plasma maintenance
5) Large hadron collider or particle accelerator. Superconductors are used to make extremely powerful electromagnets to accelerate charged particles very fast (near the speed of light).