Applied Physics for CSE Stream

Module 4

SUPERCONDUCTIVITY

Dependance of Resistivity of a metal on temperature

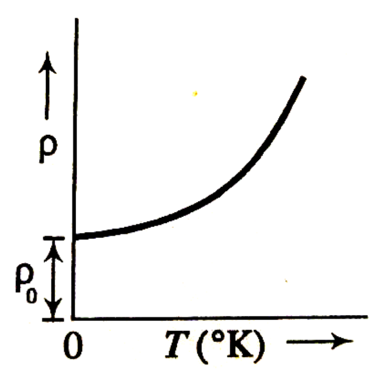
The resistance offered by a metal conductor to the flow of current is caused by scattering of the free electrons by lattice vibrations. As the temperature of a metal increases, the amplitude of the lattice vibrations thereby increasing the resistance of the metal.

The resistance decreases with decrease in temperature and reaches a minimum value at T =0. This resistance is known as **residual resistance**, due to impurities in the metal.

If a metal has more impurity, larger is the residual resistivity. The variation of resistivity with temperature is given by **Matthiessen's rule**,

$$\boldsymbol{\rho = \rho_0 + \rho\,(T)}$$

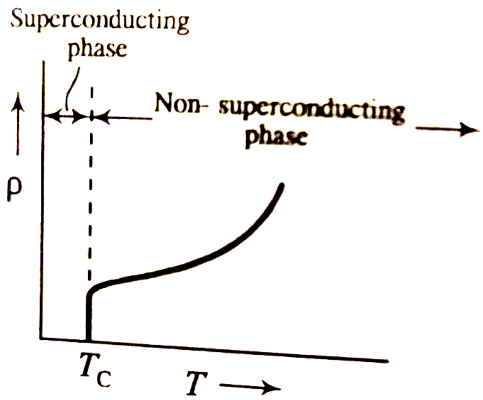
Where ρ is the resistivity of the given metal, ρ_0 is the residual activity, and $\rho\,(T)$ is the temperature dependent part of resistivity. It can be represented by graph as below,



Introduction to Superconductors: The resistance offered by certain metals, alloys, and chemical compounds to the flow of electric current abruptly drops to zero below a threshold temperature. This phenomenon is known as Superconductivity and the threshold temperature is called as critical temperature.The materials which exhibit superconductivity are called **Superconductors.**

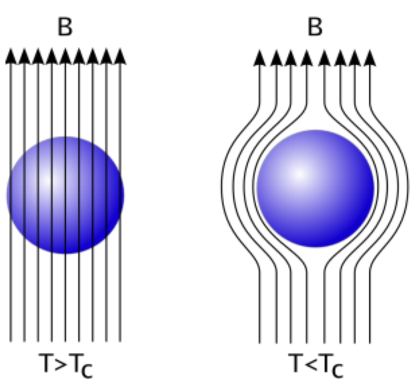
Temperature dependence of Resistivity

The variation of resistance of a superconductor with temperature is shown in the figure. The resistance of a superconductor in non-superconducting state decreases with temperature and at a particular temperature the resistance drops suddenly to zero.



The temperature at which the resistance of a material becomes zero and the material undergoes transition from normal state to superconducting state is called **Critical temperature T_c.**

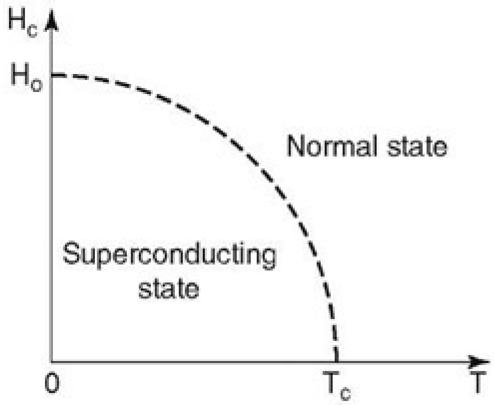
Meissner's effect



When a superconducting material is kept in in a magnetic field and cooled below the critical temperature, the magnetic flux lines are expelled from the body of the material and the material behaves like a perfect Diamagnetic. This effect is known as **Meissner effect.** The experiments of Meissner established that as the temperature is lowered, the specimen enters superconducting state. At $T < T_c$ the magnetic flux is expelled out of it.

Temperature dependence of Critical field: The superconducting state of a metal exists only in a particular range of temperature and field strength. Superconductivity vanishes if the temperature of the material is raised above critical temperature T_c or if a sufficiently strong magnetic field is applied.

The minimum magnetic field which is necessary to regain the normal state from superconducting state at a given temperature is called the Critical field H_c.



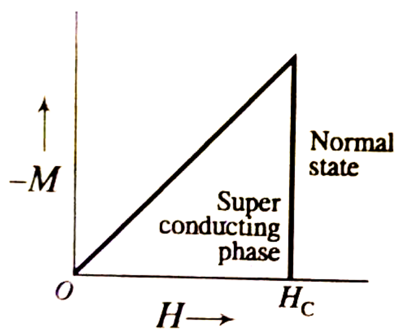
Critical field is function of temperature. If "T" is the temperature of the superconducting material ($T < T_C$). "H_c" is the critical field and "H_0" is the field required to turn the superconductor to normal conductor at 0K. Relation between H_c and H_0 is given by

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

<u>Types of Superconductors</u>

Superconductors are classified into two categories, namely Type I superconductors and Type II superconductors.

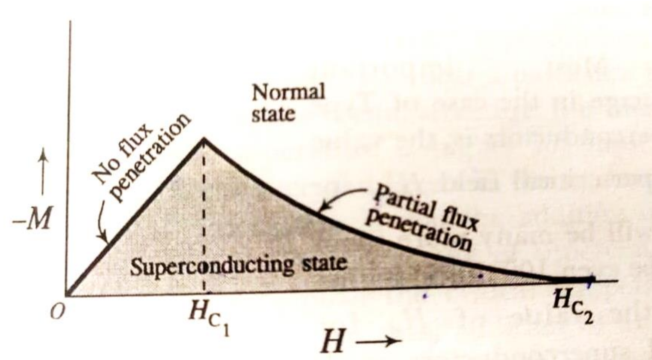
<u>Type I superconductors</u>



- Type I superconductors are called soft superconductors.
- They exhibit complete Meissner effect when $H<H_c$ and the superconducting material behaves as a perfect diamagnetic material.
- Transition from superconducting state to normal state in the presence of magnetic field occurs sharply at critical value H_c.
- When $H > Hc$ the magnetic flux enters the material, and it loses its diamagnetic property and the material comes to normal state.

- The critical field of Type I superconductors are relatively low. Aluminium, lead, and indium are examples of Type I superconductor.

<u>Type II Superconductors</u>



- They are known as hard superconductors and do not obey meissner effect.
- They are characterized by two critical fields H_{c1} and H_{c2}
- The magnetic flux does not penetrate into the specimen upto H_{c1}. Hence, it behaves as a diamagnetic material.
- At H_{c1} the magnetic flux begins to penetrate the sample, and this increases upto H_{c2}.
- At upper critical field H_{c2}, the magnetisation vanishes, and the sample reaches normal state.
- In the region between H_{c1} and H_{c2}, the superconductor is in a mixed state known as **vortex state**.
- In vortex state, the material is magnetically in mixed state but electrically it is a superconductor.
- Transition metals and alloys consisting of niobium, aluminium, silicon and vanadium exhibit type II superconductivity.

<u>BCS theory</u>

Bardeen, Cooper, and Schrieffer gave a theory to explain the phenomenon of superconductivity known as BCS theory.

- When an electron leaves an atom, it become positively charged particle (ion).
- During the flow of current in the superconductor, when an electron approaches a positive ion of the metal lattice, there is coulomb attraction between ion and the electron.

- This produces distortion in the lattice (i.e. positive ion gets displaced from its mean position).
- This distortion gives rise to phonon. This interaction called the electron-phonon interaction.
- The distortion causes an increase in the density of ions in the region of distortion. It in turn attracts another electron through phonons.
- A pair of electrons formed by the interaction between the electrons with opposite spin and momenta in a phonon field is called **Cooper pair.**
- When the electrons flow in the form of Cooper pair in materials, they do not encounter any scattering and thereby resistance reduces to zero which is known as Superconductivity.
- The cooper pairs form a collective state, which is an ordered state of the conduction electrons. They smoothly sail over the lattice point without any exchange of energy. Hence the substance possesses infinite conductivity.

High temperature Superconductivity

"Superconductors having higher critical temperatures are called high temperature superconductors".

All high temperature superconductors are not pure metals, but they are different types of oxides of copper. A warm superconductor was developed at a critical temperature of 30 K, a compound containing lanthanum, barium, copper and oxygen. High temperature superconductors are also developed with a complex unit cell structure called perovskite structures. The cell consists of 1 atom of rare-earth metal, 2 atoms of barium, 3 atoms of copper and 7 atoms of oxygen. These are popularly referred to as 1-2-3 superconductors. In early 1987, University of Alabama announced superconductivity at about 92 K in an oxide of yttrium, barium and copper ($Y_1Ba_2Ca_3O_7$). Later scientists from Japan and US reported superconductivity at 105 K in an oxide of bismuth, strontium, calcium, and copper. High temperature superconductors cannot be explained based on BCS theory.

Quantum tunneling

We know that when an electromagnetic wave strikes at the interference of two media, it is partly reflected and partly transmitted through the interface and enters the second medium. In a similar way the de Broglie wave also has a probability of partly reflected from the barrier or transmitting through the barrier. The penetration of a barrier by a quantum particle is called **Quantum tunnelling.**

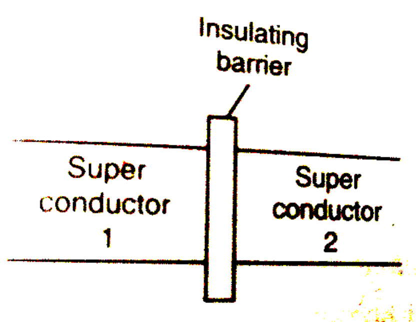
Josehpson junction

A Josephson junction is simply an arrangement of two superconductors separated by an insulating barrier. When the barrier is thin enough, cooper pairs from one superconductor can tunnel through the barrier and reach the other superconductor. Based on this theory, Josephson proposed that this kind of tunneling leads to two kinds of effects, namely

1. DC Josephson effect
2. AC Josephson effect

DC Josephson effect

Consider a Josephson junction consisting of two superconducting metal films separated by a thin oxide barrier of 10 to 20Å thick. Let it be connected in a circuit as shown in figure.



The cooper pairs in a superconductor can be represented by a wave function tunnel from one side of the junction to the other side easily. Due to the insulating layer a phase difference is introduced between the cooper pairs on either side of it.

Due to phase difference, a super current appears across the junction even though the applied voltage is zero. This is known as **dc Josephson junction Effect.** Super current through the junction is given by

$$I_s = I_C \sin \emptyset_0$$

Where $\emptyset_0$ the phase difference between wave functions describing cooper pairs is I_s is the super current and I_C is the critical current.

Note: I_C depends on the thickness and width of the insulating layer.

The Ac Josephson Effect

If we apply a dc voltage across the Josephson junction, it introduces an additional phase on cooper pairs during tunnelling. As a result new phenomenon will be observed. The dc voltage generates an alternating current I given by

$$I = I_C \sin(\emptyset_0 + \Delta\emptyset) \quad \ldots\ldots\ldots\ldots (1)$$

Because of dc voltage applied across the barrier, the energies of the cooper pairs on both the sides of the barrier differ by 2eV.

It can be shown that,

$$\Delta\emptyset = 2\pi t \left(\frac{2eV}{h}\right) \ldots\ldots\ldots\ldots (2)$$

Eqn. (1) can be written as

$$I = I_C \sin\left[\emptyset_0 + 2\pi t \left(\frac{2eV}{h}\right)\right] \ldots\ldots. (3)$$

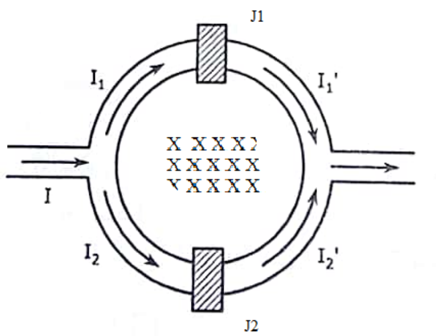
Eqn. (3) represents an alternating current of frequency $\gamma = \frac{2eV}{h}$ …. (4)

From eqn. (4) it is understood that a photon of frequency γ is absorber or emitted when the cooper pair crosses the junction. In simple, when a dc voltage is applied across Josephson junction, an ac current is produced across the junction. This is known as **ac Josephson junction effect**.

SQUIDS

A superconducting Quantum Interference device (SQUID) is a device used to measure extremely weak magnetic fields of the order of$10^{-14}\ Tesla$. It basically consists of a superconducting ring which contains one or more Josephson junctions.

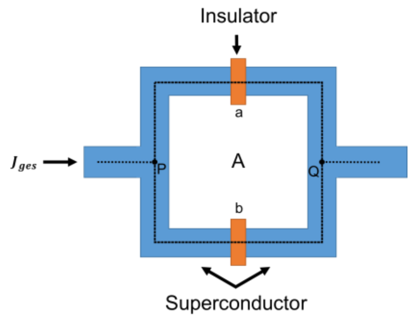
A Squid is formed by incorporating two Josephson's junctions in the loop of a superconducting material. When a magnetic field is applied to this superconducting circuit, it induces a circulating current which produces just that much opposing magnetic field as to exclude the flux from the loop. The flux remains excluded as long as the junction currents to not exceed a critical value. But the circuit switches to resistive phase and thereby the flux phases into the loop once the current in either of the junctions or in both exceed the critical value. Thus, in essence, the loop acts like a gate to allow or exclude the flux.



DC SQUID

Consider a loop with two Josephson junction as shown in the figure. Let the arrangement be placed in magnetic field.

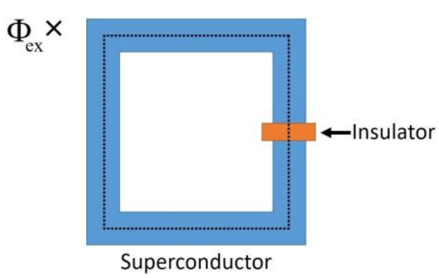
Using the arrangement, magnetic flux present in Loop between the junctions can be measured. With extreme precision due to the unique Properties of Josephson junction.



RF SQUID

As opposed to the DC SQUID, which has two junctions, the RF SQUID is composed of just one junction. To fully account for the behaviour of the RF SQUID, we must look at the inductance of a Josephson junction in an external field.

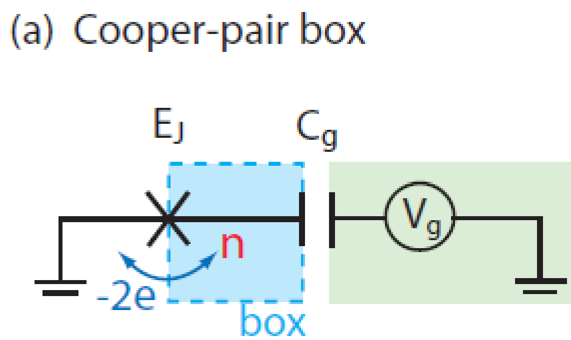
The RF (Radio Frequency) SQUID is a one-junction SQUID loop that can be used as a magnetic field detector. Although it is less sensitive than the DC SQUID, it is cheaper and easier to manufacture and is therefore more commonly used. The Quantum Design SQUID Magnetometer that is frequently used by experimenters for example, uses a one loop RF SQUID.



Applications in Quantum Computing

Charge qubit

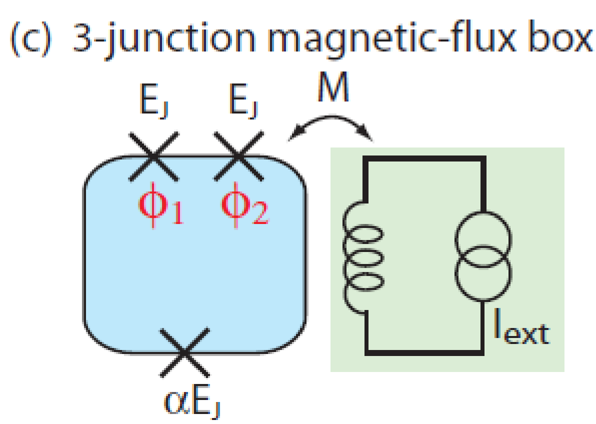
The charge qubit is based on a small superconducting island known as cooper-pair box (CPB) which is coupled to the outside world using one or two Josephson junction and driven by a voltage source as shown in the figure.



The Cooper- pair box is driven by an applied voltage V_g through the gate capacitance C_g to induce an offset charge. A Josephson junction is denoted by 'x' connects the box to the wire lead. A current driven magnetic field pierces the box with the strength given by mutual inductance and prompts stored electron pairs in and out of CPB.

Flux Qubit

A flux qubit consists of superconducting loop with three junctions and the Josephson coupling energy is much larger than charging energy of each junction. When a magnetic field is applied through the loop, a clockwise or anticlockwise supercurrent is induced to decrease or increase the



enclosed flux.

Phase Qubit

Phase qubit usually uses a large current-biased Josephson junction. The bias current produces a tilt to the Josephson potential.