CHAPTER TOW

SUPERCONDUCTOURS MATERIAL

(2.1)Introduction:

Superconductivity was discovered in 1911 by Dutch physicist Heike Kimberling Onnes by studying the resistivity of solid mercury at cryogenic temperatures using the recently discovered liquid helium as a refrigerant. After this discovery of superconductivity many metals and alloys had shown superconductivity when these specimen are cooled to sufficiently low temperature. Superconducting materials are very important in scientific and technological prospective. Some technological innovations benefiting from the discovery of superconductivity [1]are:

Magnetic resonance imaging. Sensitive magnetometer based on SQUIDS, Beam-steering magnets in particle accelerator. ,Micro wav e filters., Electronic power transmission cables .and Magnetic levitation devices

(2. 2) Historical background

In the history of superconductivity few important milestones are:

- In 1911 Dutch physicist Heike Kammerlingh Onnes by studying the resistivity of solid mercury at cryogenic temperatures using the liquid helium as a refrigerant discovered superconductivity[1][4].
- In1933 the basic physics for the understanding of superconductivity was developed by Meissner and Ochsenfeld, called Meissner effect.
- In 1950, Ginzburg-Landau develop a theory known as Ginzburg-Landau theory to explain the microscopic properties of superconductors.

- In the same year, Maxwell and Reynolds et.al. found the critical temperature dependence relation with the isotopic mass of the constituent element.
- The complete microscopic theory of superconductivity was finally proposed in 1957 by Barden, Cooper and Schrieffer by their theory known as BCS theory.
- A new era in the study of superconductivity began in 1986 with the discovery of high critical temperature superconductor and introduced the outstanding challenges of theoretical condensed matter physics

(2.3) Properties of superconductors

(2.3.1) Electromagnetic properties

(a)Zero Resistivity :The fact that the resistance is zero has been demonstrated by sustaining currents in superconducting lead rings for many years with no measurable reduction. An induced current in an ordinary metal ring would decay rapidly from the dissipation of ordinary resistance, but superconducting rings had exhibited a decay constant of over a billion years![3].

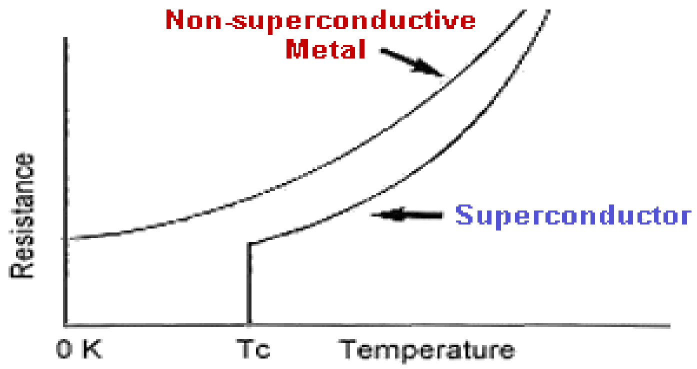


Figure (2.1) explain behavior resistivity and tem. In superconductor and normal material [4].

(b) Meissner effect or Diamagnetism:

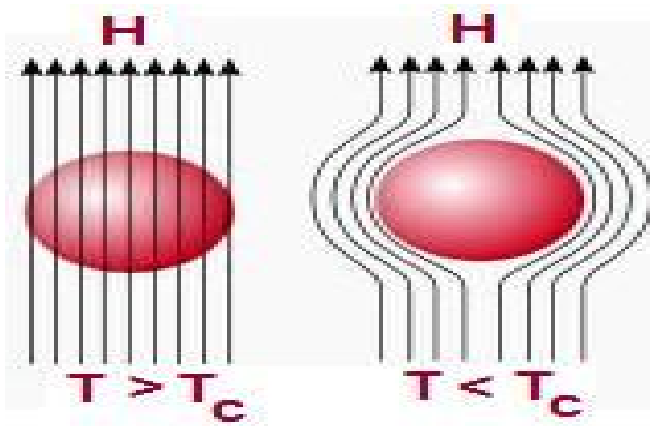
The complete ejection of magnetic flux from the specimen when they are cooled through the transition temperature in a magnetic field is known as Meissner's effect. The applied magnetic field, below transition temperature, get to magnetize the substance in an opposite direction, so it shows a negative magnetic susceptibility. Since there is complete expulsion of magnetic flux, so superconductors are perfectly diamagnetic. [1][2]

$$\chi = \frac{M}{H} = -1 \qquad (2.1)$$

Where, H :strength of the field

M : magnetization or intensity of magnetization

χ : susceptibility of the material .



Fig(2.2) Meissner Effect in Superconducting Sphere [2]

(c) Critical field :

The value of the magnetic field at which the superconductivity vanishes is called the critical field, H_c. In superconductors, their normal resistance may be restored if a magnetic field greater than the critical value; H_c is applied to the specimenH_c .

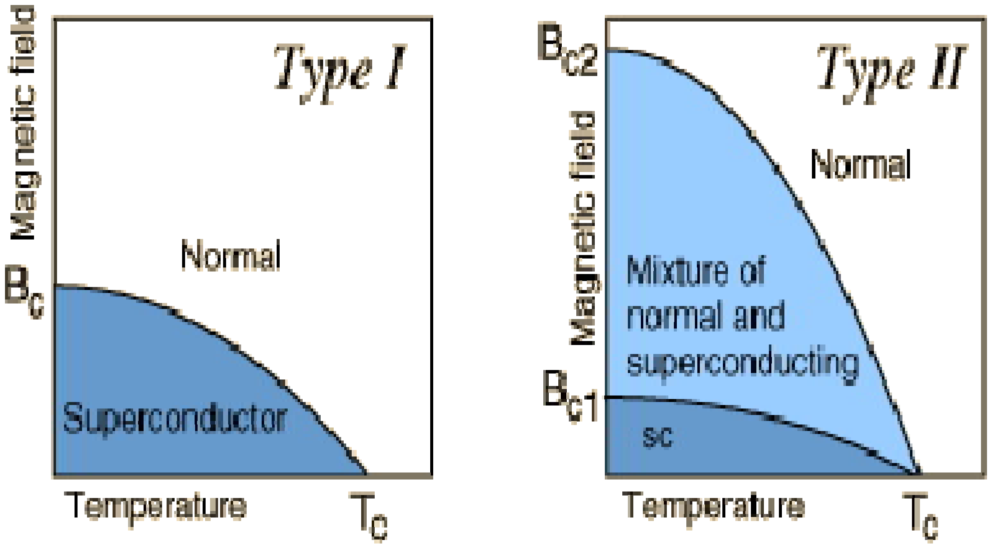
depends on the nature of material and also with the critical temperature (T_c).At critical temperature the critical field is zero and the critical field at any temperature below the critical temperature is calculated from the relation:

$$H_c = H_c(0)\,[1-((\frac{T}{T_c})^2)] \qquad (2.2)$$

Here H_c: maximum critical field strength at temperature T.

$H_c(0)$: maximum critical field strength occurring at absolute zero.

In general for higher value of H_c, the T_c value is lower and vice versa[1].



Figure(2.3) Magnetic phase diagram of type I Superconductor and type II superconductors [4].

(d)Critical current :

The minimum current for which the super conductivity retains in the sample is called the critical current I_c. Hence if a superconductor carries a current such that the field which it produces is H_c, then the resistance of the sample is restored or the material becomes normal. The critical current I_c will decrease linearly with increase of applied field upto zero[1].

(e)Flux quantization :

London, in 1950, speculated that magnetic flux penetrating through a superconducting ring or a hollow superconducting cylinder can have values equal to nh/e, where n is an integer[1].

The flux quantization has been confirmed experimentally, but the quantum of flux has been found to be h/2e rather than h/e .This unit of flux is called a fluxed.

(f) Josephson Effect :

Josephson observed some remarkable effects associated with the tunneling of superconducting electrons through a very thin insulator (1-5 nm) sandwiched between two superconductors. Such an insulating layer forms a weak link between the superconductors which is referred to as the Josephson junction.

(i)The dc Josephson Effect: A dc current flows across the junction without any application of voltage.

(ii)The ac Josephson Effect: An application of rf voltage along with the dc voltage can result in the flow of direct current through the junction. Hence this effect has been

utilized to measure e/h very precisely and may be used as a means of establishing a voltage standard .

(2.3.2) Thermal properties :

(a)Entropy: A marked decrease in entropy is observed during normal to superconductivity transition near the critical temperature which indicates that the superconducting state is more ordered than normal state. Figure (2.2) (a) explain the entropy with temperature[1][6].

(b)Specific heat From the specific heat study of superconductor we can get the information about the existence of the band gap in superconductors [3]. As we know specific heat of normal metal [1][6].

$$C_n = C_e + C_l \tag{2.4}$$

Where C_e : specific heat of the electrons:

C_l : Contribution of lattice vibration at low temperature .And γ is coefficient of the specific heat electronic is defined by :

$$\gamma = \frac{2}{3}\pi^2 K_B^2 \, N(0) \tag{2.5}$$

K_B: Boltizman constant

N(0): electron density of state at Farmi surface at T = 0K

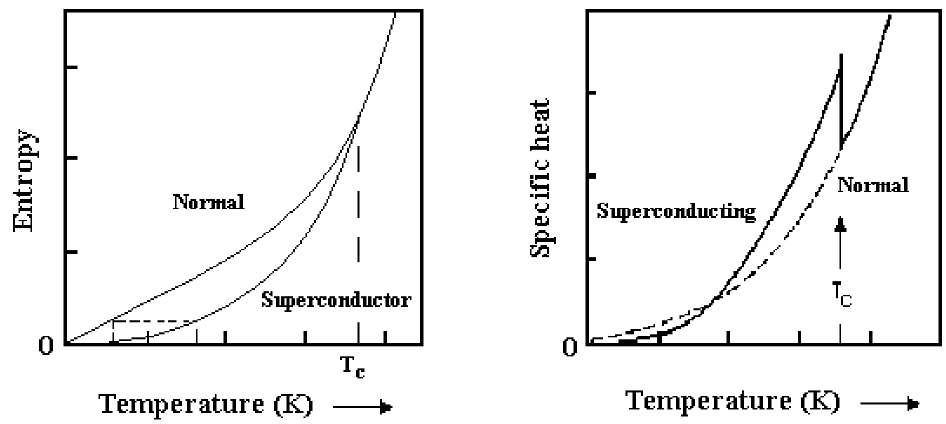
β Is coefficient associated with Debye temperature (Θ_D):

$$\beta = \frac{12}{5}\frac{\pi^4 \; NK_B}{\Theta_D^3} \tag{2.6}$$

Specific heat of superconductor shows a jump at T_c since the superconductivity affectselectron mainly. So, the lattice vibration part remains unaffected. By this substitution the electronic specific heat C_{es}shows the exponential curve [1][6].

$$C_{se}\,(\mathrm{T}) = e^{-(\frac{\Delta}{K_B T})} \tag{2.7}$$

and this indicates the existence of finite gap in the superconductor. .



(a) **(b)**

Figure (2.4) relationship between temp. And entropy (a), tem. And specific heat (b) [4].

(c)Isotope effect: in the year 1950 the dependence of transition temperature of superconductor with its isotopic mass M was given:

$$T_c \propto M^{-\frac{1}{2}} \quad (2.8)$$

The Debye temperature, θ_D of the phonon spectrum is related to M as :

$$\theta_D M^{\frac{1}{2}} = \text{constant} \quad (2.9)$$

$$T_c \propto \theta_D \propto M^{-\frac{1}{2}} \quad (2.10)$$

This sign indicates that the lattice vibration or the electron-phonon interaction plays an important role for the occurrence of superconductivity[1].y and this prediction gives the idea that two electrons in a metal can effectively attract each other, and this attraction is mediated by lattice vibration

(2.3.3) BCS Theory :

The understanding of superconductivity was advanced in 1957 by three American physicists John Bardeen, Leon Cooper and Robert Schrieffer, through a theory known as BCS theory. The BCS theory explains superconductivity at temperature close to absolute zero. A key conceptual element in this theory is the pairing of electrons by special type of attraction close to the Fermi level. These pair of electrons is called Cooper pairs [1][4] and they formed through interaction within the cryptal lattice. The idea is if we consider an electron passing close to an ion, there will be a momentary attraction between them and due to this the ion is set in motion and consequently distorts the lattices. This in turn could interact with a second electron nearby which will also be attracted to the ion. Thus we interpret that the two electrons interact via the lattice distortion or the phonon field resulting in the lowering of 6electron energy implies that the force between the two electrons is attractive. This type of interaction is called electron-lattice- electron interaction . The BCS theory is able to explain all the properties shown by the superconductor.

(2.3.4) Coherence length :

One of the characteristic lengths for the description of superconductor is called the coherence length. It interprets the approximate size of the cooper pair. It can be defined as; the maximum distance up to which the states of pair electron are correlated[1] to produce superconductivity is called coherence length ε0. It is related to the Fermi velocity for the material and

the energy gap[1][2]associated with the condensation to the superconducting state.

The superconductivity coherence length is given by :

$$\xi_0 = \frac{\hbar v_f}{\pi \Lambda(T)} \qquad (2.11)$$

Where, h is the reduced plank constant, m is the mass of the cooper pair,v_f is the velocity of cooper pair, Δ is superconducting energy gap According to BCS theory it defend by[6] :

$$\Delta(\mathrm{T}) = 3.52\ T_c K_B \qquad (2.12)$$

(2.3.5)Penetration depth:

In 1935 F. London and H. London described the Meissner effect and zero resistivity of the superconducting material by taking E=0 and B=0 in the Maxwell's electromagnetic equation. According to this the applied field does not suddenly drop to zero at the surface of the Superconductor but decay ex potentially according to the equation.

$$B = B_0\, e^{-\frac{x}{\lambda_L}} \qquad (2.13)$$

In superconductor, the London penetration depth , $\lambda_L$characterizes the distance to which a magnetic field penetrates into a superconductor and become equal to 1/e times that of the magnetic field at the surface of the superconductor and is given by[1]

$$\epsilon_0 = \left(\frac{\epsilon_0\, c^2 m}{n_e^2} \right)^{\frac{1}{2}} \qquad (2.14)$$

Where, λ_L can be distance across in which the magnetic field becomes ‘e’ times weaker .

The ratio of London penetration depth to the coherence length is:

$$K = \frac{\lambda}{\epsilon_0} \qquad (2.15)$$

is a number and changes in value from type I to type II superconductor.

For type I superconductor k$<\frac{1}{\sqrt{2}}$ and type II superconductor k$>\frac{1}{\sqrt{2}}$

(2.4)Classification of superconductors

Superconducting materials are classified into several categories according to the following considerations:

magnetic response: According to their response to magnetic field they are classified into two types:

Type I superconductors-They have a single critical field and above which the material become normal. They are pure and easily give away their superconductivity at lower field strength so referred as known as soft superconductors.

Type II superconductors -They have two critical field. It follows from the graph that for field less than H_{c1}, the material exhibit perfect diamagnetism and the flux penetration does not takes place. Thus for H<H_{c1}, the material exhibit in the superconducting state. If the field more than H_{c1} is pass through the specimen, the flux begins to penetrate the specimen and for H=H_c, the complete penetration occurs and the material become a normal conductor. As relatively large field are needed to bring these superconductor to normal state, so they are also called as hard superconductors [1][5]

The theory :According to the response of BCS theory they are classified as:

I. Conventional: They are explained by BCS theory, generally having low T_c hence called as low T_c superconductor.

II. Unconventional: They do not follow BCS theory. They show high T_c than the conventional superconductor, so generally known as high $T_c$superconductor.

The material :

I. Chemical elements

II. Alloys(niobium, titanium or germanium-niobium)

III. Ceramics(YBCO, magnesium diboride)

IV. Organic superconductors(Fullerenes, carbon nanotubes).

(2.5) High – T_c superconductors:

It has long been a dream of scientists working in the field of superconductivity to find a material that becomes a superconductor at room temperature. A discovery of this type will revolutionize every aspect of modern day technology such as power transmission and storage, communication, transport and even the type of computers we make. All of these advances will be faster, cheaper and more energy efficient. This has not been achieved to date. However, in 1986 a class of materials was discovered by Bednorz and Muller that led to superconductors that we use today on a bench-top with liquid nitrogen to cool them. Not surprisingly, Bednorz and Muller received the Nobel Prize in 1987 (the fastest-ever recognition by the Nobel committee). The material we mostly use on bench-tops is Yttrium–Barium – Copper Oxide, or $YBa_2cu_3O_7$, otherwise known as the 1-2-3 superconductor, and are classified as high temperature (T_c) superconductors. The critical temperature of some high-T superconductors[1][6]. Critical temperatures as high as 135 K have been achieved. Whilst this is not room temperature, it has made experiments on superconductivity accessible to more people since these need only be cooled by liquid nitrogen (with a boiling point of liquid nitrogen is 77 K), which is cheap and readily available. This is in contrast to the expensive and bulky equipment that used liquid helium for cooling the traditional types of superconductors. Moreover, the superconductors are calculated to have an upper critical magnetic field, B, of about 200 Tesla – huge! The crystal lattice structure of $YBa_2CU_3O_7$ is shown in Figure (2.5). Unlike traditional superconductors, conduction mostly occurs in the planes containing the copper oxide. It has been found that the critical temperature is very sensitive to the average number of oxygen atoms present, which can vary. For this reason the formula for superconductor is sometimes given as a$YBa_2Cu_3O_{7-\delta}$ where δ is number between 0 and 1. The nominal distance between cooper pairs (coherence length) in these superconductors can be as short as one or two atomic spacing. As a result, the coulomb repulsion force will generally dominate at these distances causing electrons to be repelled rather than coupled. For this reason, it is widely accepted that Cooper pairs, in these materials, are not caused by a lattice deformation, but may be associated with the type of magnetism present (known as anti ferromagnetism) in the copper oxide layers. So high–T_c superconductors cannot be explained by the BCS theory that mainly deals with a lattice deformation mediating the coupling of electron pairs. The research continues into the actual mechanism responsible for superconductivity in these materials [6].

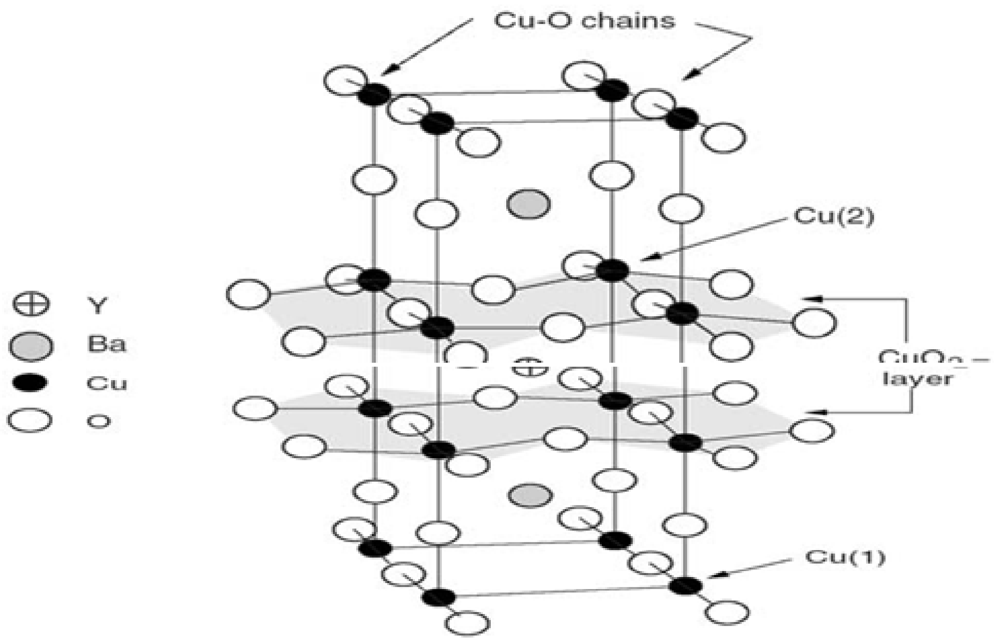


Figure (2.5): Crystal lattice structure of the High – T_c superconductor, $YBa_2Cu_3O_7$ [4].

(2.6)Applications of superconductors:

The first large scale commercial application superconductivity was in magnetic resonance imaging (MRI). This is a non-intrusive medical imaging technique that creates a two-dimensional picture of say tumors and other abnormalities within the body or brain. This requires a person to be placed inside a large and uniform electromagnet with a high magnetic field. Although normal electromagnets can be used for this purpose, because of resistance they would dissipate a great deal of heat and have large power requirements. Superconducting magnets on the other hand have almost no power requirements apart from 3O7coperating the cooling. Once electrical current flows in the superconducting wire, the power supply can be switched off because the wires can be formed into a loop and the current will persist indefinitely as long as the temperature is kept below the transition temperature of the superconductor. Superconductors can also be used to make a device known as a superconducting quantum interference device (SQUID). This is incredibly sensitive to small magnetic fields so that it can detect the magnetic fields from the heart (10-10 Tesla) and even the brain (10-13 Tesla). For comparison, the Earth's magnetic field is about 10-4 Tesla. As a result, SQUIDs are used in non-intrusive medical diagnostics on the brain. The traditional use of superconductors has been in scientific research where high magnetic field electromagnets are required. The cost of keeping the [1][7],

superconductor cool are much smaller than the cost of operating normal electromagnets which dissipate heat and have high power requirements. One such application of powerful electromagnets is in high energy physics where beams of protons and other particles are accelerated to almost light speeds and collided with each other so that more fundamental particles are produced. It is expected that this research will answer fundamental questions such as those about the origin of the mass of particles that make up the Universe .Levitating trains have been built that use powerful electromagnets made from superconductors. The superconducting electromagnets are mounted on the train. Normal electromagnets, on a guide way beneath the train, repel (or attract) the superconducting electromagnets to levitate the train while pulling it forwards. A use of large and powerful superconducting electromagnets is in a possible future energy source known as nuclear fusion. When two light nuclei combine to form a heavier nucleus, the process is called nuclear fusion.

This results in the release of large amounts of energy without any harmful waste. Two isotopes of hydrogen, deuterium and tritium, will fuse to release energy and helium. Deuterium is available in ordinary water and tritium can be made during the nuclear fusion reactions from another abundantly available element – lithium. For this reason it is called clean nuclear energy. For this reaction to occur, the deuterium and tritium gases must be heated to millions of degrees so that they become fully ionized. As a result, they must be confined in space so that they do not escape while being heated. Powerful and large electromagnets made from superconductors are capable of confining these energetic ions. An international fusion energy project, known as the International Thermonuclear Experimental Reactor (ITER) is currently being built in the south of France that will use large superconducting magnets and is due for completion in 2017. It is expected that this will demonstrate energy production using nuclear fusion[1][7].