Chapter (1)
Introduction for Superconductors

1.1 Definition of superconductors:

Superconductivity is not a new phenomenon which has been discovered in 1911. [1]
It occurs in certain materials at low temperatures, characterized by the complete absence of electrical resistance. Superconductor is an element, intermetallic-alloy or compound that will conduct electricity with very low resistance below a certain temperature (close to absolute zero).

The use of HTS components enables increases in both sensitivity and selectivity due to extremely low losses in the materials. Advantages of HTS devices include that they can be smaller in size and weight and more efficient in conducting electricity. [2]

A superconductor can conduct electricity with very low electrical resistance at temperatures above absolute zero. The change from normal electrical conductivity to superconductivity occurs abruptly at a critical temperature T_c as shown in figure 1.1. [3].

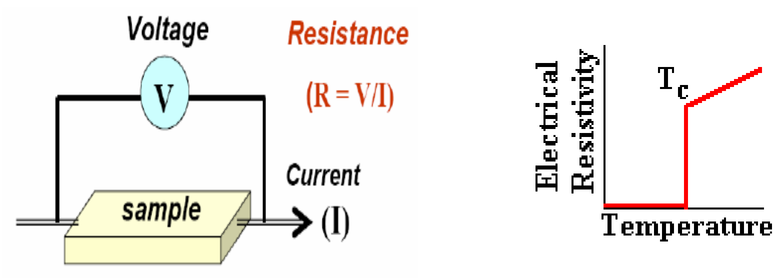


Figure (1.1) Electric resistivity Vs Temperature

Superconductivity is destroyed by increasing the temperature at T>T_c and by large magnetic field where H>H_c as shown in figure 1.2.

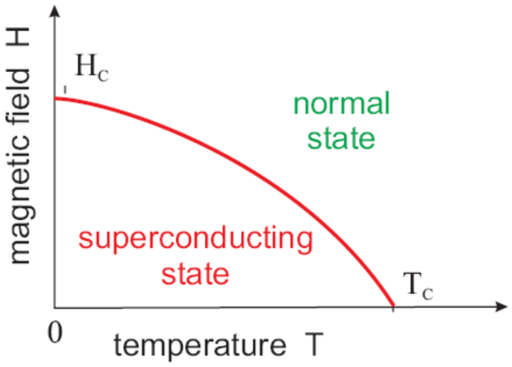


Figure (1.2) H-T diagram for superconducting state.

When a small, strong magnet exposed to a superconductor, it induces a current in the superconductor. Because the current flows inside the superconductor without electrical resistance, the current induces its own magnetic field which can repel the magnet, producing a force to counteract gravity in order to levitate the magnet above the surface of the superconductor.

A superconductor is also able to exclude the surrounding magnetic field. This is known as the Meissner Effect shown in figure 1.3. [4]

In the simplest case, when a permanent magnet (PM) is placed over a superconductor, the magnetic field produced by the PM is repelled by an equal and opposite field produced by the superconductor. This causes the PM to levitate above the superconductor as shown in figure 1.4. [5]

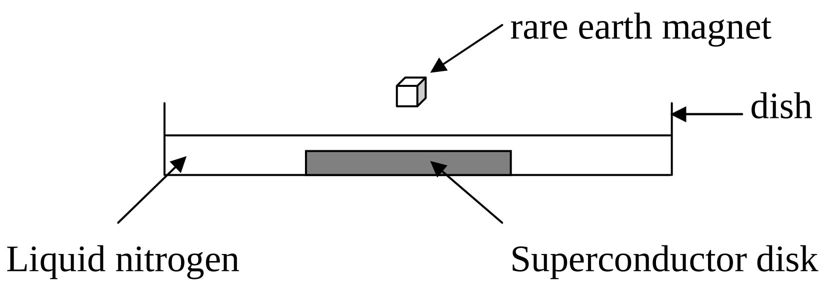


Figure (1.3) Meissner effect

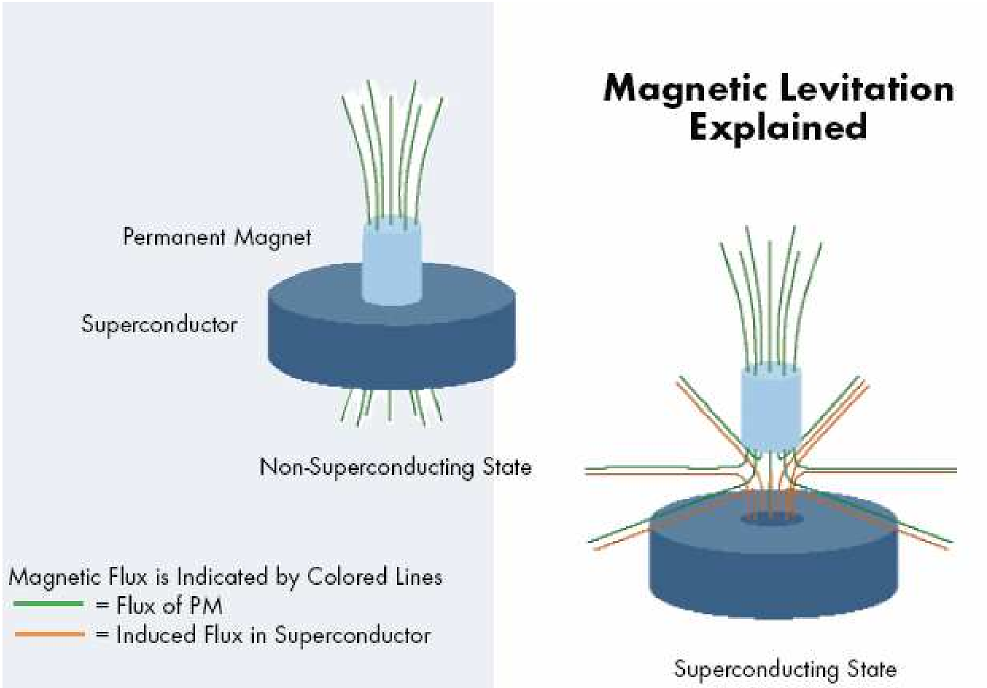


Figure (1.4) Superconducting theory

1.2 History:

In 1911 superconductivity was first observed in mercury (Hg) having T_c =4.2K by Dutch Physicist Heike Kamerlingh Onnes. [6]
When liquid mercury was cooled to liquid helium temperature (4.2 degrees Kelvin) its resistance suddenly disappeared. (The resistance was coming down linearly until it dropped to zero ohms).For this discovery, he was awarded the Nobel Prize on physics in 1913.

Superconductivity was found in several other materials. Lead was found to superconduct at 7k, and in 1941 niobium nitride was found to superconduct at 16k. [1], [6]

In 1933, the next step in understanding the superconductivity when Meissner and Oschenfeld discovered that superconductors expelled applied magnetic fields, phenomena which was known as the Meissner effect. [1], [6]

In 1950, Abrikosov showed that Ginzburg-Landau theory predicts the division of superconductors into two categories now referred to as Type I and Type II. [1], [6]
Both scientists were awarded the Nobel Prize for these works in 2003, and both types will be discussed later in section 1.5

In 1962, Bednorz and Mueller discovered superconductivity in a lanthanum-based cuprate perovskite material, which had a transition temperature of 35k (Nobel Prize at 1987). It was shortly found that replacing the lanthanum with yttrium, i.e. making Yuttirium Barium Copper Oxide (YBCO), raised the critical temperature to 92k, which was important because liquid nitrogen could then be used as refrigerant (at atmospheric pressure, the boiling point of nitrogen is 77k). [1], [6]

In 1972, Nobel Prize for physics which was called BCS theory proposed that electrons form pairs (known as cooper pairs) in the superconductor and these pairs are able to carry current without losses. [1], [6]

Year	Event
1911	Superconductivity discovered (Onnes).
1933	Meissner effect discovered (Meissner).
1934	Phenomenological theory (London).
1950	Macroscopic Quantum theory.
1957	Prediction of Type 2 materials &BCS
1961	High-field, High-current properties
1962	Josephson effect predicted &discovered
1986	HTS (Tc=35K).
1987	HTS (Tc=93K).
1988	HTS (Tc=110-125K).
1993	HTS (Tc=150 K)
2003	Macroscopic theory of superconductivity
Till now	HTS is increased every year

Table (1.1) Important dates in the history of the superconductivity.

pure metals

material	T_c,K	H_c,Oe	year
Al	1.2	105	1933
In	3.4	280	
Sn	3.7	305	
Pb	7.2	803	1913
Nb	9.2	2060	1930

alloys

material	T_c,K	H_c,Oe	year
NbN	15	$1.4\ 10^5$	1940
Nb_3Ge	23	$3.7\ 10^5$	1971

ceramics

material	T_c,K	year
$La_{1.85}Ba_{0.15}CuO_4$	35	1986
$YBa_2Cu_3O_7$	93	1987
$Bi_2Sr_2CaCu_2O_{8+x}$	94	1988
$Ta_2Ba_2Ca_2Cu_3O_{10+x}$	125	1988
$HgBa_2Ca_2Cu_3O_{8+x}$	150^*	1993

$*$ under pressure

Table (1.2) Some materials with different T_c's [7]

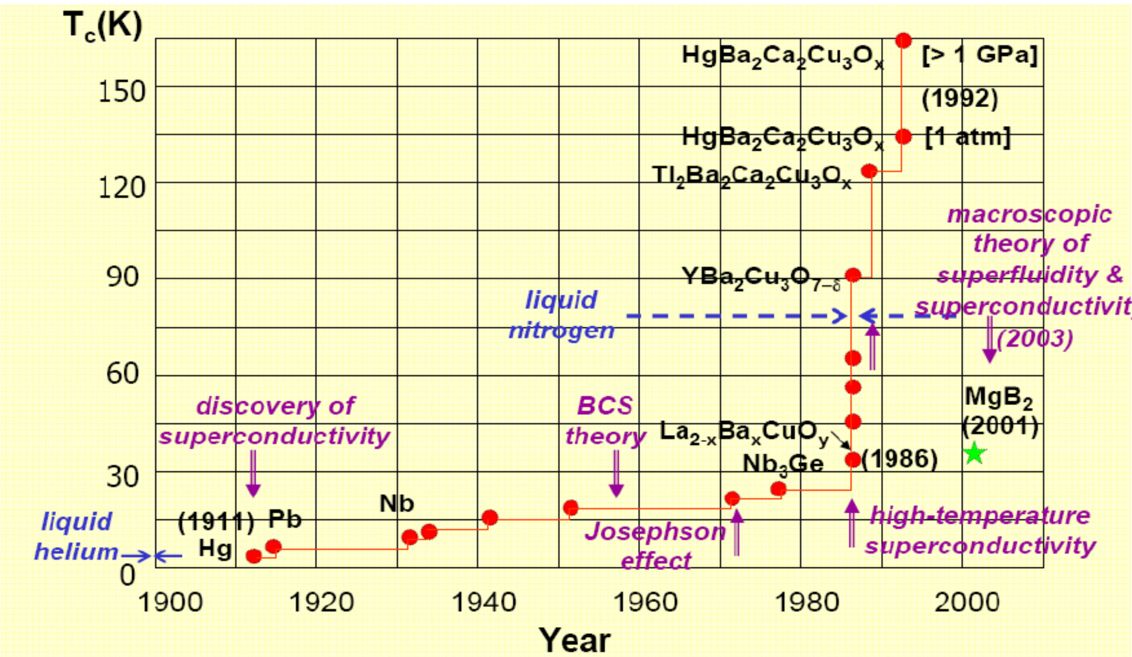


Figure (1.5) The time evolution of maximum superconductor critical temperature (Tc) & significant events in the research development of superconductors. [3]

1.3 Advantages & limitations of using superconductors:

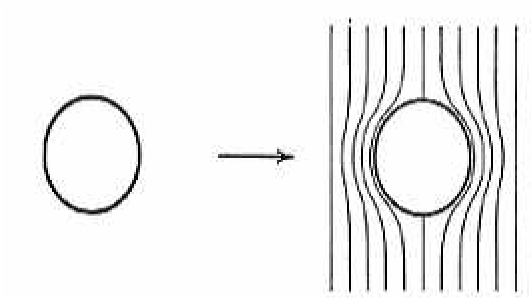
- Superconductors and their applications provide significant advantages as indicated in the following examples: [4]
   i. Superconductors have low insertion losses and gives high selectivity and sensitivity.
   ii. Superconductors are small in size and light in weight.
   iii. Superconductors carry large currents with no heat loss and can generate very strong magnetic fields.
   iv. Superconductors have beneficial applications in medical imaging techniques. SQUIDs (Superconducting QUantum Interference Devices) are sensitive enough to detect the very weak magnetic fields caused by electrical currents in the human brain. The devices have allowed doctors to develop better images of brain disorders.
   v. Superconductors have been used in Japan to make experimental, magnetically levitated trains.
   vi. Electric generators made with superconducting wire are far more efficient, and about half the size, than conventional generators wound with copper wire.
   vii. New superconductive films may result in the miniaturization and increased speed of computer chips.

- The limitations of superconductors include the technical difficulties of achieving and reliably sustaining the extremely low temperatures required to achieve superconductivity. The materials, of which they are made, are often brittle, are hard to manufacture and they are difficult to make into wire.

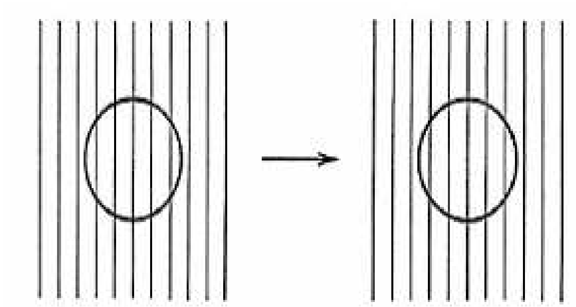
1.4 Comparison between the perfect conductor and the superconductor: [8]

The illustrated figure (1.6) explains the difference between perfect conductor and superconductors.

Perfect conductor



Case (1) The specimen is first cooled below its transition temperature and then brought into magnetic field.

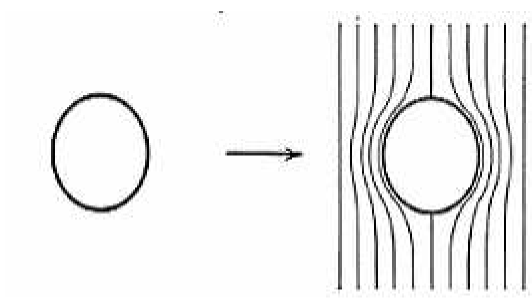


Case (2) The specimen is brought into magnetic field while it is in the normal state and subsequently cooled below its transition temperature.

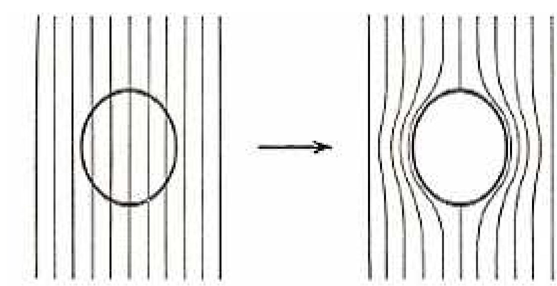
The behavior expected for a transition into a state of perfect conductivity. The final state would depend on the serial order in which the specimen is brought into the same external conditions.

$$\frac{\partial B}{\partial t} = 0$$

Superconductors



Case (1) The specimen is first cooled below its transition temperature and then brought into magnetic field.



Case (2) The magnetic field is applied while the specimen is in the normal state, the field is pushed out when the specimen is cooled below its transition temperature.

According to Meissner: The superconductor in contrast to the perfect conductor, has zero magnetic induction independently of the way in which the superconducting state has been reached.

$$\beta = 0$$

Figure (1.6) Perfect conductor and superconductor

1.5 Superconductor Types:

Type 1 superconductors (Low-T_c) and a periodic chart comparison: [1]

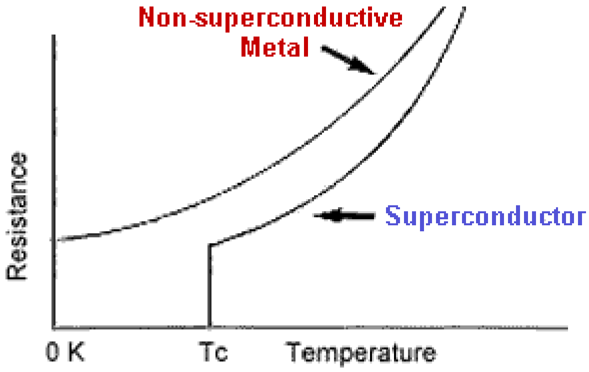


Figure (1.7) Resistance Vs Temperature for type 1

The Type 1 category of superconductors is mainly comprised of metals and metalloids that show some conductivity at room temperature.

Type 1 superconductors - characterized as the "soft" superconductors - were discovered first and require the coldest temperatures to become superconductive. They exhibit a very sharp transition to a superconducting state (see figure 1.7) and the ability to repel a magnetic field completely. [1]

Type 2 superconductors (High -T_c): [1]

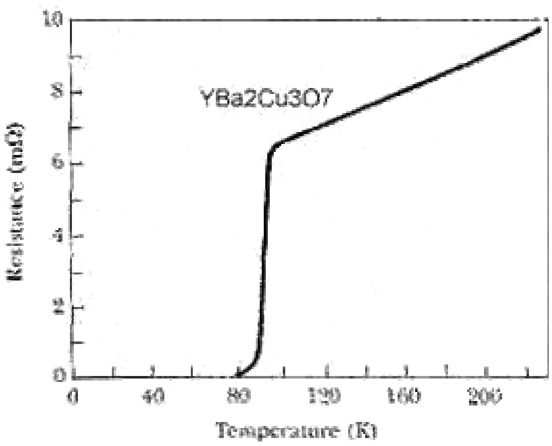


Figure (1.8) Resistance Vs Temperature for type 2

All known high-Tc superconductors are so-called Type 2 superconductors and also called “hard superconductors”, and are comprised of metallic compounds and alloys.
Type 2 achieves higher Tc's than Type 1 superconductors and they exhibit much higher critical magnetic fields. Figure 1.8 represents the Type 2 superconductor curve between resistance Vs temperature.
The current record for Tc is 138K ($Ba_2Ca_2Cu_3O_{8.33}$).
Yuttrium Barium Copper Oxide (YBCO) is considered a Type 2 superconductor.
Type 1 superconductor (London superconductor) is comprised of pure metals and alloys while Type 2 superconductor (Pippard superconductor) is comprised of impure metals. [1]

1.6 Characteristics of High Temperature Superconductors (HTS):

High-temperature superconductivity is changing the way we design communication systems, electronic systems, medical instrumentation, and military microwave systems. Superconducting filters play an important role in many applications, especially those for the next generation of mobile communication systems. Most superconducting filters are simply microstrip structures using HTS thin films. For the design of HTS microstrip filters, it is essential to understand some important properties of superconductors and substrates for growing HTS films. [9]

Transition temperatures of well-known superconductors (Boiling point of liquid nitrogen for comparison)

Transition Temperature (in Kelvin)	Material	Class
138	$Hg_{12}Tl_3Ba_{30}Ca_{30}Cu_{45}O_{127}$	Copper-oxide superconductors
110	$Bi_2Sr_2Ca_2Cu_3O_{10}$(BSCCO)	
92	$YBa_2Cu_3O_7$ (YBCO)	
77	Boiling point of liquid nitrogen	
43	SmFeAs(O,F)	Iron-based superconductors
41	CeFeAs(O,F)	
26	LaFeAs(O,F)	
20	Boiling point of liquid hydrogen	
18	Nb_3Sn	Metallic low-temperature superconductors
10	NbTi	
4.2	Hg (Mercury)	

Table (1.3) Transition temperature for some LTS and HTS

1.6.1 Superconducting properties:

There are three properties that are important to understand when discussing the superconductor materials. [9]

1- The critical temperature (T_c) below which a superconductor reaches a zero resistance and above which the material is in normally resistive state.
2- The critical current density (J_c) which indicates the maximum current that a superconductor can carry without destroying its superconductive state.
3- The critical magnetic field (H_c) is the maximum magnetic field a superconducting material can tolerate.

1.6.2 Superconducting materials and substrates:

Superconductors are materials that exhibit a zero intrinsic resistance to direct current (DC) flow when cooled below a certain temperature. Superconductors made from different materials have different T_c values.

Superconductors that are most frequently used for microwave applications:

$YBa_2Cu_3O_{7-d}$ (YBCO), its T_c is about 92k while for $Tl_2Ba_2CaCuO_8$ (TBCCO) is about 105k [10]. YBCO is a very common Type 2 superconductor. YBCO compounds, also known as 1-2-3 compounds, are very sensitive to oxygen content. They change from semiconductors at $YBa_2Cu_3O_{6.5}$ to superconductors at $YBa_2Cu_3O_7$ without losing their crystalline structure.

Most of the materials have a very low T_c and therefore cooling to the temperature of liquid helium 4.2K is usually required. HTS materials with a critical temperature above the boiling point of liquid nitrogen (77K) were soon discovered.
Most of the HTS materials consist of CuO planes separated by layers of other elements or oxides. All of the compounds consist of at least three different chemical elements and the materials with the highest T_c have seven elements in the crystal lattice. One of the most famous HTS materials is YBCO. YBCO is a chemical compound with the formula $\mathrm{YBa_2Cu_3O_7}$. This material is the most famous "High Temperature Superconductor". It was the first material to achieve superconductivity above the boiling point of nitrogen (77K). YBCO has high threshold temperature of around 92K and the magnetic field can be as high as 300T. For thin-film applications, critical current density (J_c) which is the maximum current that a superconductor can carry is an important parameter and in the case of YBCO, it is typically $J_c \rangle$ 1MA/cm^2 which is a very large value.
YBCO and TBCCO are the two most popular commercially available.
BSCCO and YBCO are two HTS ceramics which are brittle.

<u>The most famous HTS materials are shown below</u>:

Materials	$T_c(K)$
$YBa_2Cu_3O_{7-x}(YBCO)$	$\cong 92$
$Tl_2Ba_2Ca_1Cu_2O_x(TBCCO)$	$\cong 105$

Table (1.4) Most famous HTS materials

Advantages of YBCO compared to other ceramic superconductors:

1-The only known stable four-element compound with a Tc of 92K (above 77K).

2-Includes neither toxic elements nor volatile compounds.

3-Less anisotropic than other HTS materials.

Preparation of YBCO:

Preparation of the superconductor material YBCO

$$\frac{1}{2}Y_2O_3 + 2BaCO_3 + 3CuO \rightarrow YBa_2Cu_3O_{6.5}$$

Extra Oxygen insertion (hole doping)

$$YBa_2Cu_3O_{6.5} \rightarrow YBa_2Cu_3O_{7-\delta}$$

HTS substrates:

A dielectric substrate (known as laminate) is a main constituent of the microstrip structure, whether it is a microstrip line, circuit or an antenna.

Design consideration substrates:

The choice of the substrate depends on the size, dielectric loss, power handling and implementation (spacing, coupling…etc.). The substrate is an integral part of the microstrip line and determines the electrical characteristics of the circuit.

The good substrate material should have uniform permittivity, uniform thickness (h) and small dielectric loss ($\tan \delta < 0.001$) in order to ensure high performance and acceptable quality factor (Q).

Material	Dielectric Constant
Alumina	8 – 10
RT/duroid microwave laminates	2.23 – 2.33
GaAs	12.8
Sapphire	9.4/11.6

Table (1.5) Dielectric constants of various materials

The surface of the substrate should be smooth and free from defects and twinning is possible. For microwave applications, it is important that the substrate have a low dielectric loss tangent ($\tan\delta$). The dielectric constant (ε_r) must be invariant against temperature changes to ensure stability.

The most widely used and commercially available substrates are LAO, MgO and Al_2O_3. [9]

$LaAlO_3$ or LAO	. Higher dielectric constant (ε_r) .Generally twinned
MgO	. Very good substrate . is mechanically brittle . is not available in large wafers.
Sapphire (Al_2O_3)	. low loss substrate . low cost substrate . ε_r is not isotropic . requires buffer layer

Table (1.6) Some substrate characteristics

Silicon is not a preferred microstrip substrate because it has low resistivity causing losses at high frequencies.

1.6.3 Complex conductivity:

Figure 1.9 describes a simple equivalent circuit which describes the complex conductivity of a superconductor. The current density J is divided into current densities carried by the paired electron (J_s) and the current densities carried by normal electron (J_n). [9]

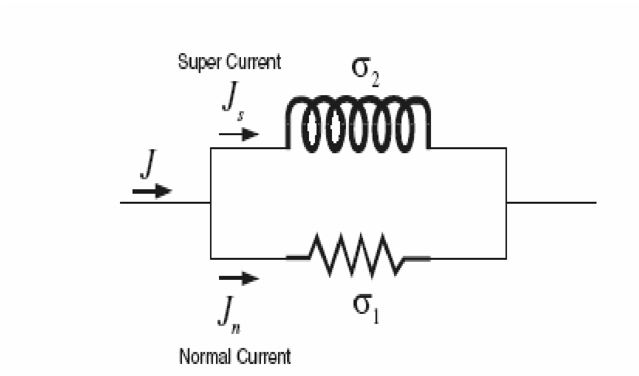


Figure (1.9) Simple circuit describe the complex conductivity

The total current in the circuit is split between the reactive inductance and the resistance, which represents dissipation. As the frequency decreases, the reactance becomes lower and more current flows through the inductance. When the current is constant at dc, this inductance is completely shorts the resistance. The complex conductivity of a superconductor is given by:

$$\sigma = \sigma_1 - j\sigma_2$$

$$= \sigma_n (\frac{T}{T_c})^4 - j\frac{1}{\omega\mu\lambda_0^2}[1-(\frac{T}{T_c})^4] \qquad (1.1)$$

Where σ_n is the normal state conductivity, λ_0 is the penetration depth at temperature approaches to absolute zero Kelvin and μ is the permeability in free space which is approximately $4\pi \times 10^{-7}$.

T and T_c are the temperature of boiling point of nitrogen (77 K) and the critical temperature of the superconducting material respectively.

1.6.4 Penetration depth & skin depth:

The penetration depth (λ_0) is defined as the characteristic depth at the surface of the superconductor such that an incident wave propagating into the superconductor is attenuated by e^{-1} of its initial value.

The penetration depth is given by the following equation:

$$\sigma_2 \rangle\rangle \sigma_1$$

$$\lambda = \frac{1}{\sqrt{\omega\mu\sigma_2}} \qquad (1.2)$$

Where λ is the penetration depth of the superconductor.

$\sigma_1 and \sigma_2$ are the conductivities of the superconductors.

Substitute σ_2 from (1) into (2)

$$\lambda = \frac{\lambda_0}{\sqrt{1-(\frac{T}{T_c})^4}} \qquad (1.3)$$

Where λ_0 is the actually penetration depth and its value is about 0.2μm for HTS. (λ_0=0.2 μm for HTS).The penetration depth is dependent on the frequency but depends on the temperature. The skin depth is defined as the depth at which the electromagnetic field penetrates the superconductor and is denoted by:

$$\sigma = \sqrt{\frac{2}{\omega\mu\sigma_n}} \tag{1.4}$$

Where σ_n is the conductivity of a normal conductor and is purely real & is independent of frequency, the skin depth is a function of frequency.

1.6.5 Surface impedance of superconductors:

The surface impedance is defined as the ratio between the tangential electric field to the tangential magnetic field. The surface impedance is given by:

$$Z_s = \frac{E_t}{H_t} = \sqrt{\frac{j\omega\mu}{\sigma}} \tag{1.5}$$

Where E_t & H_t are the tangential electric & magnetic fields respectively at the surface [9]. For superconductors, replacing σ by $\sigma_1 - j\sigma_2$ gives

$$Z_s = \sqrt{\frac{j\omega\mu}{(\sigma_1 - j\sigma_2)}} \tag{1.6}$$

Whose real and imaginary parts are separated, where

$$Z_s = R_s + jX_s \tag{1.7}$$

Where $K = \sqrt{\sigma_1^2 + \sigma_2^2}$

For superconductors: $R_s = \dfrac{\omega^2\mu^2\sigma_1\lambda^3}{2}$ and $X_s = \omega\mu\lambda$ (1.8)

It is important to note that for the two-fluid model, provided σ_1 & λ are independent of frequency, the surface resistance R_s will increase as ω^2. Figure 1.10 illustrates typical temperature dependence behaviors of R_s, where R_0 is a reference resistance.

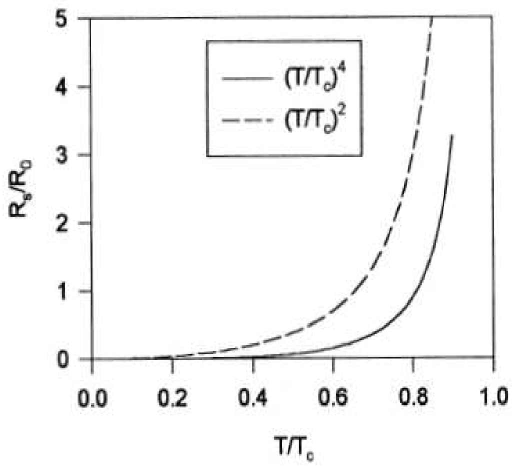


Figure (1.10) Temperature dependence of surface resistance of superconductor

For normal conductor: The surface resistance & surface reactance are equal & are given by the equation

$$R_s = X_s = \sqrt{\frac{\omega\mu}{2\sigma_n}} \qquad (1.9)$$

and both are proportional to the square root of frequency.

Figure 1.11 shows the comparison of the surface resistance of YBCO at 77k with copper, as a function of frequency. The typical values used to produce this plot are:

*YBCO thin film surface resistance (10 GHz and 77 K) = 0.25 mΩ

*Copper surface resistance (10 GHz and 77 K) = 8.7 mΩ

*Copper surface resistance (10 GHz and 300 K) = 26.1 mΩ

In this case, the crossover frequency between copper and HTS films at 77 K is about 100 GHz.
It is also be seen from the figure that at 2GHz the surface resistance of HTS thin film at 77k is a thousand times smaller than that of copper at 300k. [9]

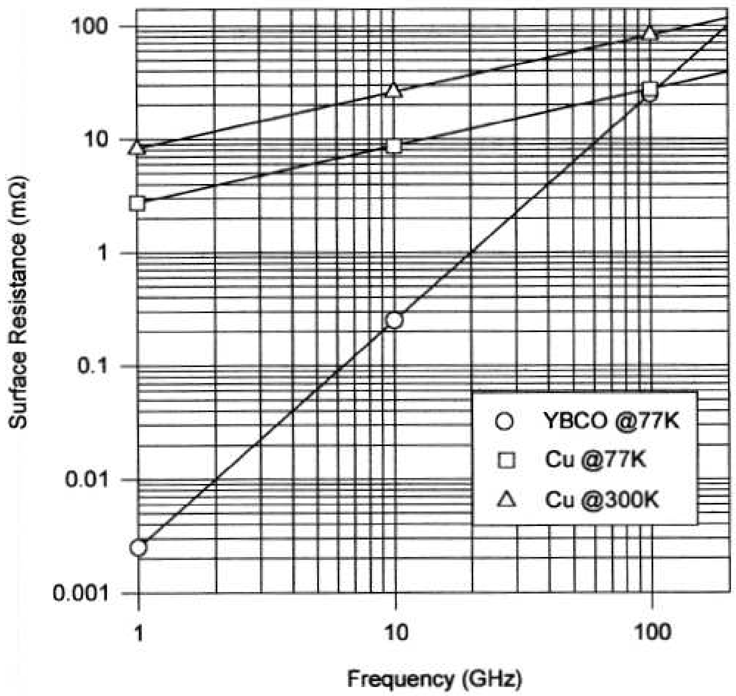


Figure (1.11) Surface resistance Vs Frequency

1.6.6 Nonlinearity of Superconductors:

Nonlinearity causes increases losses of HTS filter, intermodulation and harmonic generation problems. This limits the power handling of HTS filters.

The power handling can be increased by two ways: [9]

1- Increasing the critical current density by improving the material or to operate filter at lower temperature. (J_c increases as the temperature decreases)

2- Reducing the maximum current density in the filter by distributing the RF/microwave current more uniformly over a large area.

High-Power HTS filters:

The above-described HTS filters are primarily for low-power applications.

HTS filters can also be designed for high-power applications. In general, there are three main factors that may limit the power handling of a RF/microwave filter which are the RF breakdown, heating and nonlinearity in the materials.

RF breakdown or arcing occurs at very high electric fields.

Reducing the concentration of the electric fields can be occurred using thicker substrate, reducing the dielectric constant (ε_r), and avoiding very small coupling gap.

Nonlinearity appears due to non linear surface resistance.

Heating is associated with dissipation in materials including dielectrics and conductors. Increasing input power of a HTS filter will arise the maximum current density at the surface of superconductor.

1.7 Applications for superconductors:

Some applications for the high temperature superconductors (HTS) are briefly discussed below. [1-10]

1-Magnetic Levitation (Maglev):

. Transport vehicles such as trains can be made to "float" on strong superconducting magnets, virtually eliminating friction between the train and its tracks. (The test attained an incredible speed of 361 mph or 581 kph).

. A combination of superconducting magnet and linear motor technology, realizes super high –speed running, safety, reliability, low enviromental impact and minimum maintenance.

Figure (1.12) Maglev train

2-Used in life-saving function in the field of biomagnetism:

MRI of a human skull
Figure (1.13) MRI

MRI is an imaging technique used primarily in medical settings to produce high quality images of the inside of human body.

3-used in electric generators:
Electric generators made with superconductivity wire are far more efficient than conventional generators wound with copper wire. In fact, their efficiency is about 99% and their size about half that of conventional generators.
HTS motors and generators offer improved energy efficiency because of their lower resistance.

4-Used in military fields:
Superconductors have also found wide spread applications in the military fields.
HTSC SQUIDS (Superconducting Quantum Interference Device) are being used by U.S. Navy to detect mines and submarines.
The U.S. air force has hit Iraqi TV with an experimental electromagnetic pulse device called "E-bomb" in an attempt to knock it off the air and shut- down Saddam Hussein's propaganda machine.

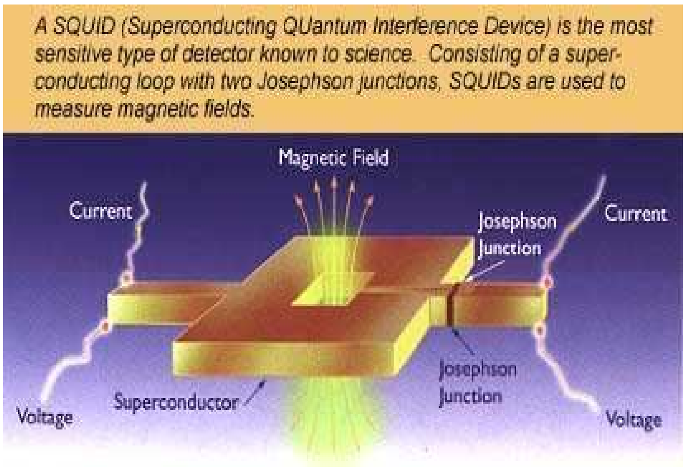


Figure (1.14) SQUID

E-bomb (Electronic-bomb):

Figure (1.15) E-bomb

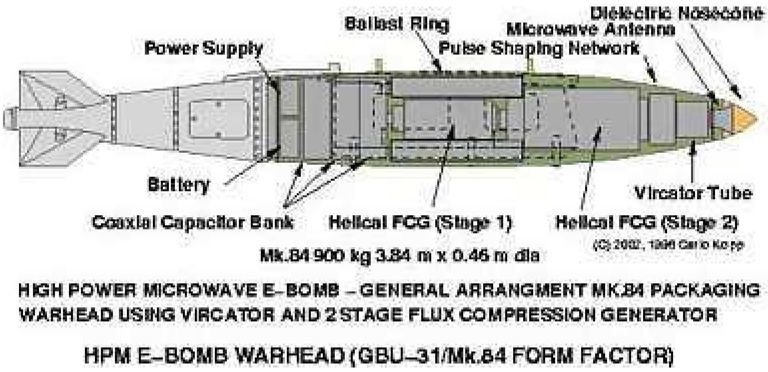


Figure (1.16) Internal components for E-bomb

5-Cellular Communications:

Superconducting filters in cellular base stations are the most advanced application of HTS films and various companies have placed commercial units on the market.

Several thousands high frequency signal filters have been installed in the base-stations of cellular networks to improve their performance.

The immediate benefits for network operators range can play an important role in rural areas or where GSM networks are upgraded to UMTS (3G filters) because these new networks usually requires smaller cell size.

6-Mobile communication: (improves sensitivity)
The aim of the future is to reduce the power, this cause to reduce the coverage area.
The solution is occurred by increasing the number of base transreciever stations (BTS) which increases the coverage area. The future 3rd generation operates at low power levels =0.2 W
Using HTS reduces the power from 40 w to 2 w, Passband loss = 0.3 dB, High adjacent channel rejection =60 dB [10].

7- Satellite communication:
Communication satellites are giant relay stations receiving weak signals from earth stations and bouncing them back after amplification. The major part of the payload of such a satellite consists of RF-filters to select signals from a broadband transmission. After amplification signals are multiplexed and returned to a receiver on earth. As the electronic systems for satellite communications increases, even more filters will be needed. To reduce the size, weight, and cost of the multiplexers without compromising performance, NASA Lewis Research Center is collaborating with industry develop a new class of dual-mode multilayer filters consisting of $YBa_2Cu_3O_{7-d}$ high temperature superconducting (HTS) thin films on $LaAlo_3$ substrates.

8-Communication filters:
YBCO superconducting filters provide an advantage of increasing sensitivity (the result of noise reduction). Advantage of superconducting filters over the conventional filters installed in base-stations is that they have a dramatically reduced size & weight.

The following ISIS graph gives a rough breakdown of the various markets in which superconductors are expected to make contribution

Economic outlook

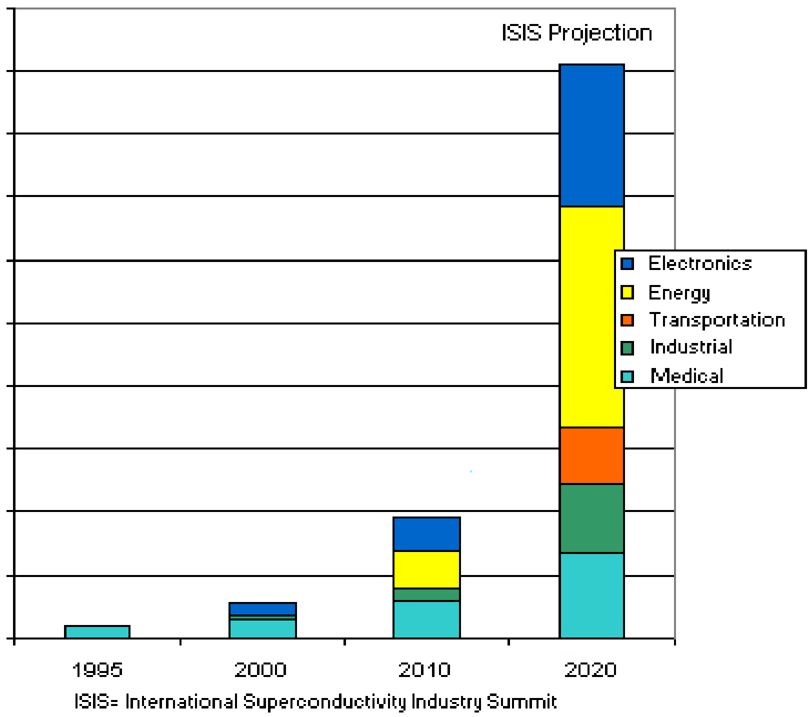


Figure (1.17) International Superconducting Industry Summit

Future Work for HTS:

By the year 2010, it is estimated that the global superconductivity market will excess of $50 billion [11]. After the discovery of the transistor in 1947, it took almost 40 years to introduce the one megabyte memory chip which is vital to today's powerful computers.

Events	Years
Development of material technology	1981-1986
Development of Application principles	1992-1996
Elaboration for prototypes	1997-2001
Coming into the market	2002-2007

Table (1.7) Four stages of progress in HTS electronics at microwaves

Years	**Sum in billion US dollars**
2010	50
2020	120

Table (1.8) Estimation of the total turnover of production based on superconductor components

Modern discoveries in superconductivity go far beyond piece-meal improvements in electric devices. They have opened the door on a totally new technology and stretch the imagination to the discovery of new applications. Future generations will witness significant changes in electricity generation, transmission and storage, impacts in microelectronics, communications and computers, and advances in solid state science.

1.8 Summary:

This chapter described the superconducting phenomena with its advantages and limitations, also it described the different types of superconductors with different applications and future works, and In addition this chapter has discussed the superconducting filters with the characteristics of HTS.