Learning Objectives

After studying this chapter, the student will be able to

- ➡ Define superconductor and critical temperature
- ➡ Understand the basic properties of superconductors
- ➡ Distinguish between Type I and Type II superconductors
- ➡ Describe the structure and composition of high temeperature superconductors
- ➡ Enlist the different applications of superconductors such as Maglev train and SQUID

8.1 INTRODUCTION

***Superconductivity** is a phenomenon in which certain metals, alloys and ceramics conduct electricity without resistance when it is cooled below a certain temperature called the critical temperature.*

Superconductivity was discovered by a Dutch physicist, Heike Kammerlingh Onnes, in 1911 and it is still an exciting field of discovery and technological applications. This new state was first discovered in mercury when cooled below 4.2 K. Since then, a large number and wide variety of metals, alloys, binary and ternary chemical compounds have been found to show superconductivity at various temperatures.

In the following sections fundamental terms and phenomena of superconductors, its properties, types and its applications are discussed in brief.

8.2 SUPERCONDUCTOR

A superconductor is a material that loses all its resistance (offers zero resistance) to the flow of electric current when it is cooled below a certain temperature called the critical temperature or transition temperature T_c.

Examples: Mercury (Hg), Zinc (Zn), Vanadium (V), Tin (Sn) and Niobium (Nb).

8.3 CRITICAL TEMPERATURE T_c (TRANSITION TEMPERATURE)

The temperature at which a material's electrical resistivity drops to absolute zero is called the critical temperature or transition temperature T_c.

At and below T_c, the material is said to be in the superconducting state and above this temperature, the material is said to be in the normal state.

Figure 8.1 shows the variation of electrical resistivity of a normal metal silver (Ag) and a superconducting metal mercury (Hg) versus temperature.

From Figure 8.1 it can be seen that the electrical resistivity of normal metal decreases steadily as the temperature is decreased and reaches a low value at 0 K *called the residual resistivity* ρ_0. But in contrast, the electrical resistivity of mercury suddenly drops to zero at critical temperature T_c and is 4.2 K for Hg.

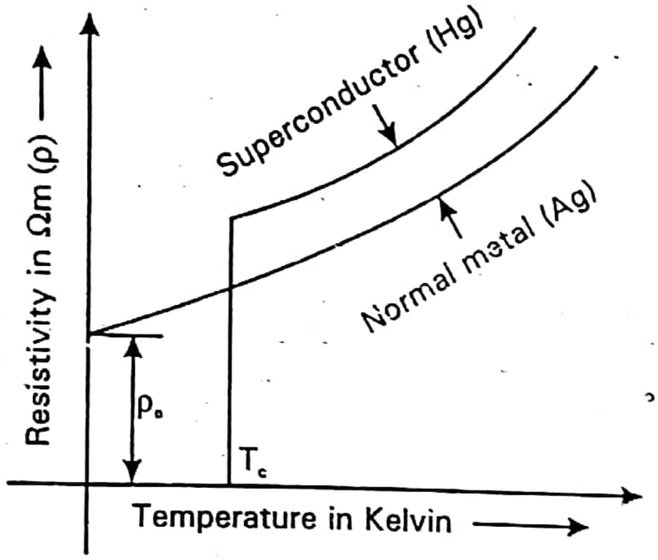

Figure 8.1: Electrical resistivity vs temperature plots for a superconductor and a normal metal

Note:

- Good electrical conductors such as silver (Ag), gold (Au) and copper (Cu) are not good superconductors because the resistivity of these conductors at low temperatures is limited to low resistivity ρ_0 (residual resistivity) value due to scattering of electrons from crystal defects and impurities.
- Similarly, good superconducting materials like Zn and Pb are not good electrical conductors.

Below the critical temperature, not only does the superconductor suddenly achieves zero resistance, it also exhibits a variety of several astonishing magnetic and electrical properties.

The T_c values for some selected metals, intermetallic and ceramic superconductors are given in Table 8.1.

Table 8.1

Metals	T_c in K	Intermetallic compounds	T_c in K	Ceramic compounds	T_c in K
Tin (Sn)	3.72	NbTi	9.5	$Y_1 Ba_2 Cu_3 O_{7-x}$	93
Mercury (Hg)	4.2	Nb_3Sn	21	Tl – Ba – Ca – Cu	125
Vanadium (V)	5.3	Nb_3Ge	23.2	HgBaCuO	133

8.4 PROPERTIES OF SUPERCONDUCTORS

Few important properties of superconductors are explained in brief in this section.

(i) Electrical resistance

The electrical resistance of a superconducting material is very low and is of the order of 10^{-7} Ωm.

(ii) Effect of impurities

When impurities are added to superconducting elements, the superconducting property is not lost, but the T_c value is lowered.

(iii) Effect of pressure and stress

Certain materials are found to exhibit the superconductivity phenomena on increasing the pressure over them. For example, cesium is found to exhibit superconductivity phenomena at T_c = 1.5 K on applying a pressure of 110 Kbar.

In superconductors, the increase in stress results in increase of the T_c value.

(iv) Isotope effects

The critical or transition temperature T_c value of a superconductor is found to vary with its isotopic mass. This variation in T_c with its isotopic mass is called the isotopic effect.

The relation between T_c and the isotopic mass is given by

$$T_c \propto \frac{1}{\sqrt{M}} \text{ where M is the isotopic mass,}$$

i.e., the transition temperature is inversely proportional to the square root of the isotopic mass of a single superconductor.

(v) Magnetic field effect

If a sufficiently strong magnetic field is applied to a superconductor at any temperature below its critical temperature T_c, the superconductor is found to undergo a transition from the superconducting state to the normal state.

This minimum magnetic field required to destroy the superconducting state is called the critical magnetic field H_c.

The critical magnetic field of a superconductor is a function of temperature. The variation of H_c with temperature is given by

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

where H_0 is the critical field at $T = 0$ K. The critical field decreases with increasing temperature and becoming zero at $T = T_c$.

Figure 8.2 shows the variation of critical field H_c as a function of temperature. The material is said to be in the superconducting state within the curve and is non-superconducting (i.e., normal state) in the region outside the curve.

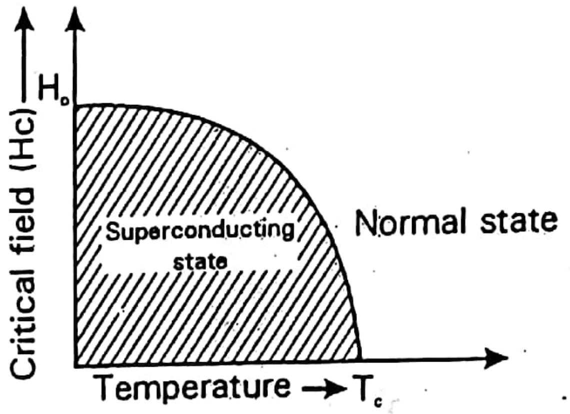

Figure 8.2: Dependence of H_c on T

(vi) *Critical current density J_c and critical current I_c*

The critical current density is another important characteristic feature of the superconducting state.

When the current density through a superconducting sample exceeds a critical value J_c, the superconducting state is found to disappear in the sample. This happens because the current through the superconductor itself generates a magnetic field, and at a sufficiently high current density the magnetic field will start exceeding the critical magnetic field H_c, thereby making the superconducting state to disappear in the material.

Hence, the critical current density can be defined as the maximum current that can be permitted in a superconducting material without destroying its superconductivity state. The critical current density is a function of temperature, i.e., colder the temperature for a superconductor the more is the current it can carry.

For a thin long cylindrical superconducting wire of radius r, the relation between critical current I_c and critical magnetic field H_c is given by

$$I_c = 2\pi r H_c$$

Similarly, the relation between critical current density J_c and critical current I_c is given by

$$J_c = \frac{I_c}{A}$$

where A is the superconducting specimen's cross-sectional area.

(vii) *Persistent current*

When current is made to flow through a superconducting ring (say a loop of lead wire), which is at a temperature either equal to its T_c value or less than its T_c value, it was observed that the current was flowing through the material without any significant loss in its value.

This steady flow of current in a superconducting ring without any potential deriving it is called the persistent current.

(viii) Meissner effect (Diamagnetic property)

The complete expulsion of all the magnetic field by a superconducting material is called the 'Meissner effect'.

When a superconducting material is placed in a magnetic field ($H > H_c$) at room temperature, the magnetic field is found to penetrate normally throughout the material (Figure 8.3(a)).

However, if the temperature is lowered below T_c and with $H < H_c$ the material is found to reject all the magnetic field penetrating through it, as shown in Figure 8.3(b).

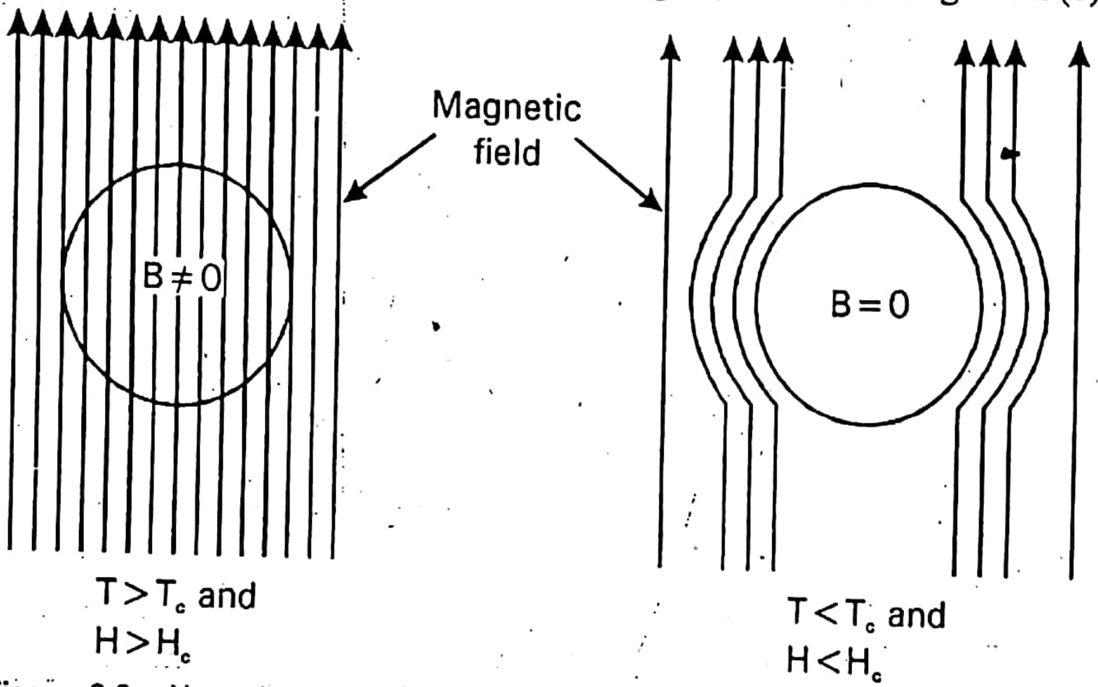

Figure 8.3a: Normal state

Figure 8.3b: Superconducting state

The above process occurs due to the development of surface current, which in turn results in the development of magnetization M within the superconducting material. Hence, as the developed magnitation and the applied field are equal in magnitude but opposite in direction, they cancel each other everywhere inside the material. Thus, below T_c a superconductor is a perfectly diamagnetic substance ($\chi_m = -1$).

The Meissner effect is a distinct characteristic of a superconductor from a normal perfect conductor. In addition, this effect is exhibited by the superconducting materials only when the applied field is less than the critical field H_c.

8.4.1 To Prove $\chi_m = -1$ for Superconductors

We know that for a magnetic material the magnetic induction or magnetic flux density B is given by

$$B = \mu_0 (M + H) \qquad ...(1)$$

where μ_0 is the permeability of free space

M is the intensity of magnetisation

and H is the applied magnetic field.

But, we know that for a superconductor $B = 0$

Therefore, equation (1) can be written as

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

$$\because \quad \mu_o \neq 0$$

$$M + H = 0$$

or

$$M = -H$$

or

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

Hence, $\chi_m = -1$ *where* $\chi_m = \dfrac{M}{H}$ *is called the magnetic susceptibility.* Thus this means that for a superconductor the susceptibility is negative and maximum, i.e., a *superconductor exhibits perfect diamagnetism.*

8.4.2 Three Important Factors to Define a Superconducting State

In general, the superconducting state is defined by three important factors:

(i) Critical temperature T_c

(ii) Critical current density J_c

(iii) Critical magnetic field H_c

Each of the above three parameters is very dependent on the other two properties. To sustain superconducting state in a material, it is required to have both the current density and magnetic field, as well as the temperature, to remain below their critical values; and all of these would depend on the material.

The relationship between T_c, J_c and H_c is shown in the phase diagram (Figure 8.4).

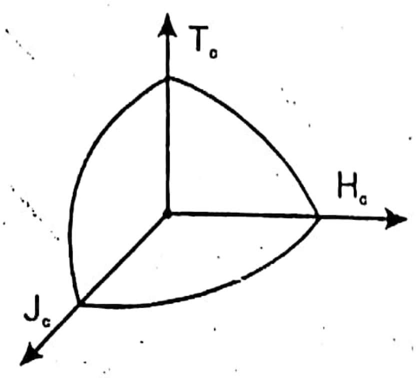

Figure 8.4: Critical surface phase diagram

The highest values for H_c and J_c occur at 0 K, while the highest value for T_c occurs when H and J are zero. Thus, the plot of all these three parameters represents a critical surface.

Within the surface the material is superconducting and outside the surface the material is said to be in the normal state.

Example 8.1

For mercury of mass number 202, the α value is 0.50 and T_c is 4.2 K. Find the transition temperature for the isotope of mercury of mass number 200.

Solution:

Given,

$$\text{Mass number } M_1 = 202$$
$$\alpha = 0.5$$
$$T_{c1} = 4.2 \text{ K}$$
$$\text{Mass number } M_2 = 200$$
$$T_{c2} = ?$$

We know, $M^\alpha T_{c1} = \text{constant}$

Using this,

$$M_1^\alpha T_{c1} = M_2^\alpha T_{c2}$$

or

$$T_{c2} = \left(\frac{M_1}{M_2}\right)^\alpha T_{c1} = \left(\frac{202}{200}\right)^{0.5} \times 4.2 \qquad \left[\because \alpha = \frac{1}{2}\right]$$

$$= 1.004987 \times 4.2$$

$$T_{c2} = \mathbf{4.2209\ K.}$$

Example 8.2

The critical temperature of Nb is 9.15 K. At zero kelvin the critical field is 0.196 T. Calculate the critical field at 6 K.

Solution:

Given, $T_c = 9.15$ K ; $T = 6$ K ; $H_o = 0.196$ T ; $H_c = ?$

$$H_c = H_o\left(1-\left(\frac{T}{T_c}\right)^2\right) = 0.196\left[\left(1-\left(\frac{6}{9.15}\right)^2\right)\right]$$

$$= 0.196\,[1 - 0.4299]$$

$$= 0.196\,[0.5701]$$

$$\therefore \quad H_c = \mathbf{0.1117\ T.}$$

Example 8.3

The critical temperature for a metal with isotopic mass 199.5 is 4.185 K. Calculate the isotopic mass if the critical temperature falls to 4.133 K.

Solution:

Given, $M_1 = 199.5$; $T_{c1} = 4.185$ K ; $T_{c2} = 4.133$ K ; $M_2 = ?$

Formula:

$$M_1^{\alpha}\ T_{c1} = M_2^{\alpha}\ T_{c2}$$

$$\therefore \quad M_2^{\alpha} = (199.5)^{\alpha}\ \frac{4.185}{4.133}$$

$$M_2^{0.5} = (199.5)^{0.5} \times 1.01258 \qquad \left[\because \alpha = \frac{1}{2}\right]$$

$$\sqrt{M_2} = \sqrt{199.5} \times 1.01258 = 14.124 \times 1.01258$$

$$M_2 = (14.301)^2$$

$$\therefore \quad M_2 = \mathbf{204.55.}$$

Example 8.4

Calculate the critical current through a long thin superconducting wire of radius 0.5 mm. The critical magnetic field is 7.2 kA/m.

Solution:

Given, $H_c = 7.2 \times 10^3$ A/m ; $r = 0.5 \times 10^{-3}$ m ; $I_c = ?$

Formula:

$$I_c = 2\pi r\ H_c$$

$$= 2 \times 3.14 \times 0.5 \times 10^{-3} \times 7.2 \times 10^3$$

$$\therefore \quad I_c = \mathbf{22.608\ A.}$$

Example 8.5

Superconducting Sn has a critical temperature of 3.7 K at zero magnetic field and a critical field of 0.0306 T at 0 K. Find the critical field at 2 K.

Solution:

Given, $T_c = 3.7$ K ; $H_o = 0.0306$ T ; $H_c = ?$; $T = 2$ K

Formula:

$$H_c = H_o\left[1-\left(\frac{T}{T_c}\right)^2\right] = 0.0306\left[1-\left(\frac{2.0}{3.7}\right)^2\right]$$

$$= 0.0306\,(1 - 0.29218) = 0.0306 \times 0.70782$$

$$\therefore \quad H_c = \mathbf{0.021659\ tesla.}$$

Example 8.6

Calculate the critical current for a superconducting wire of lead having a diameter of 1 mm at 4.2 K. Critical temperature for lead is 7.18 K and $H_c(0) = 6.5 \times 10^4$ A/m.

Solution:

Given, $H_o = 6.5 \times 10^4$ A/m ; $T_c = 7.18$ K ; $r = 0.5 \times 10^{-3}$ m ; $T = 4.2$ K ; $I_c = ?$; $H_c = ?$

Formula:

$$H_c = H_o\left[1-\left(\frac{T}{T_c}\right)^2\right] = 6.5 \times 10^4\left[1-\left(\frac{4.2}{7.18}\right)^2\right]$$

$$= 6.5 \times 10^4 (1 - 0.34217) = 6.5 \times 10^4 \times 0.65783$$

$$\therefore \quad \mathbf{H_c = 42.758\ kA/m.}$$

$$I_c = 2\pi r H_c = 2 \times 3.14 \times 0.5 \times 10^{-3} \times 42.758 \times 10^3$$

$$\therefore \quad \mathbf{I_c = 134.26\ A.}$$

Example 8.7

The critical field for vanadium is 10^5 Am^{-1} at 8.58 K and 2×10^5 Am^{-1} at 0 K. Determine the T_c value.

Solution:

Given, $H_c = 10^5\ Am^{-1}$; $H_o = 2 \times 10^5\ Am^{-1}$; $T = 8.58$ K ; $T_c = ?$

Formula:

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

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

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

$$\therefore \quad T_c = \frac{T}{\sqrt{1-\left(\frac{H_c}{H_o}\right)}} = \frac{8.58}{\sqrt{1-\frac{10^5}{2\times10^5}}} = \frac{8.58}{\sqrt{1-0.5}} = \frac{8.58}{\sqrt{0.5}} = \frac{8.58}{0.7071}$$

$$\therefore \quad \mathbf{T_c = 12.1334\ K.}$$

8.5 TYPES OF SUPERCONDUCTORS

Based on the behaviour of superconducting materials in an applied magnetic field, the superconductors are classified into type I and II superconductors.

8.5.1 Type I Superconductors

Type I superconductors exhibit complete Meissner effect, i.e., they are completely diamagnetic. The magnetization curve for type I superconductor is shown in Figure 8.5(a). The values of H_c for type of I superconducting materials are always too low.

The magnetization curve shows that the transition at H_c is reversible. This means that if the magnetic field is reduced below H_c, the material again acquires superconducting property and the field is expelled.

Type I superconductors are also called as ***soft superconductors*** because of their tendency to allow the field penetration even for a lower applied field. Many pure elements, alloys and some compound superconductors exhibit type I behaviour.

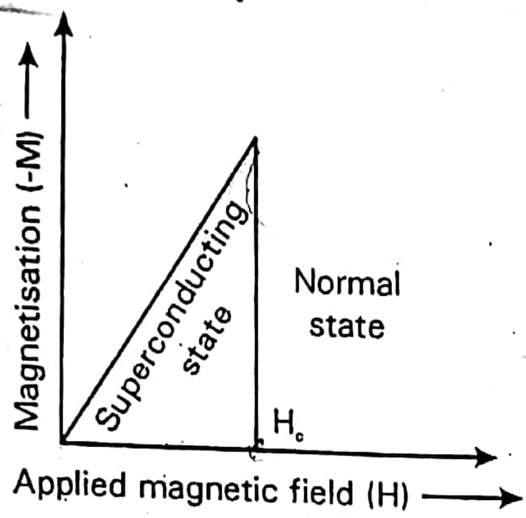

Figure 8.5a: Type I superconductor

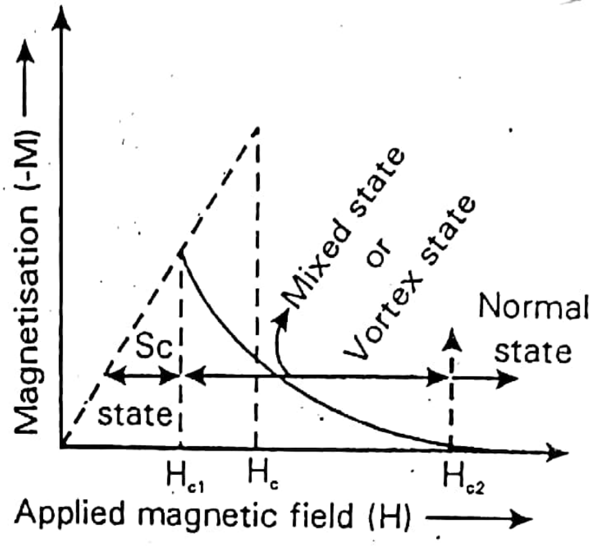

Figure 8.5b: Type II superconductor

8.5.2 Type II Superconductors

Type II superconductors behave differently in an increasing field, as shown in Figure 8.5(b). For an applied field below H_{c1}, the material is perfectly diamagnetic and hence the field is completely excluded. *H_{c1} is called as lower critical field.* At H_{c1}, the field starts to thread the specimen and this penetration increases until H_{c2} is reached at which the magnetization vanishes and the specimen becomes normal. *H_{c2} is called the upper critical field.*

In the region between H_{c1} and H_{c2} the material is in the mixed state or the vortex state. The value of H_{c2} for type II may be 100 times more or even higher than that of type I superconducting material. As H_{c2} and T_c of type II superconducting materials are higher than that of type I superconductors, the type II superconducting materials are most widely used in all engineering applications.

Type I superconducting materials are also called as ***hard superconductors*** because of relatively large magnetic field requirement to bring them back to their normal state.

Examples for type I and type II superconducting materials with their H_c values are listed in Table 8.2.

Table 8.2: Examples of type I and type II superconducting materials

Type I		Type II	
Material	*H_c in tesla*	*Material*	*H_c in tesla*
Ta	0.083	$Y_1 Ba_2 Cu_3 O_7$	300
Pb	0.08	$Ba_{2-x} B_x Cu O_4$	150
Hg	0.014	Nb_3Sn	24.5
Sn	0.030	$Nb_3 Ge$	38

8.6 COMPARISON BETWEEN TYPE I AND TYPE II SUPERCONDUCTORS

	Type I superconductor		*Type II superconductor*
1.	These superconductors are called as soft superconductors.	1.	These superconductors are called as hard superconductors.
2.	Only one critical field exists for these superconductors.	2.	Two critical fields H_{c1} (lower critical field) and H_{c2} (upper critical field) exist for these superconductors.
3.	The critical field value is very low.	3.	The critical field value is very high.
4.	These superconductors exhibit perfect and complete Meissner effect.	4.	These do not exhibit a perfect and complete Meissner effect.
5.	These materials have limited technical applications because of very low field strength value. *Examples:* Pb, Hg, Zn, etc.	5.	These materials have wider technological applications because of very high field strength value. *Examples:* Nb_3Ge, Nb_3Si, $Y_1Ba_2Cu_3O_7$, etc.

8.7 HIGH T_C SUPERCONDUCTORS

Based on the coolants to achieve superconductivity phenomena in materials, the superconductors fall in two categories:

1. Low-temperature superconductors
2. High-temperature superconductors

8.7.1 Low-Temperature Superconductors

Superconductors that require liquid helium as coolant are called low-temperature superconductors (LTS or Low – T_c). Liquid helium temperature is 4.2 K above absolute zero.

8.7.2 High-Temperature Superconductors

Superconductors having their T_c values above the temperature of liquid nitrogen (77 K or –196°C) are called the high-temperature superconductors (HTS or High-T_c).

After the discovery of superconducting in mercury (4 K) by Heike Kammerling onnes, the critical temperature had been gradually increased from 4 K of Hg to 23 K in the compound Nb_3Ge, which was first discovered in 1973. This remained a record until 1986.

On January 27, 1986, a new era of superconductivity science and technology began. J. George Bednorz and K.A. Muller, using a variant of the materials synthesized by Michel, smashed the long-stand 23 K temperature record with a compound of barium, lanthanum, copper and oxygen, that at 30 K is a very indicator of superconductivity.

Similar materials with higher transition temperature (High-T_c) soon followed in the history of superconductors when $Y_1Ba_2Cu_3O_{7-\delta}$ (Y BCO) or the so-called 1-2-3 compound was discovered in 1987. The 1-2-3 compound was the first oxide superconductor to have transition temperature above liquid nitrogen temperature.

Soon after the discovery of superconductivity in YBCO material, more than 50 superconducting cuprates are now known. Extensive research to find high-T_c superconductivity in other families of materials has been unsuccessful. The highest transition temperature, currently known is 138 K, in a thallium-doped mercuric cuprate comprises the elements Hg, Tl, Ba, Ca, Cu and oxygen.

Examples for High-temperature superconductors are listed in Table 8.3.

Table 8.3: Examples of high-temperature superconductors

S. No.	Material	T_c's in K
1.	$Pb_2 YSr_2 Cu_3 O_8$	77
2.	Y – Ba – Cu – O ($Y_1Ba_2 Cu_3 O_7$)	93–95
3.	Tl (Bi) – Ba(Sr) – Ca – Cu – O	122–125
4.	Hg – Ba – Ca – Cu – O	130–135

8.8 APPLICATIONS OF SUPERCONDUCTORS

8.8.1 Magnetic Levitation (Maglev)

Magnetic levitation or maglev is the process by which an object is suspended above another object with no other support but magnetic fields.

We know that a diamagnetic substance repels a magnetic field. Thus, the perfect diamagnetic property of superconductors make them suitable for achieving frictionless motion in motors and bearing.

The phenomena of magnetic levitation is based on Meissner effect.

How to achieve magnetic levitation?

The magnetic levitation is brought about by enormous repulsion between two highly powerful magnetic fields.

If a small magnet is brought near a superconductor it will be repelled. This repulsion takes place due to the induced currents in the superconductor which is being generated by the magnetic field of the magnet. Because of zero resistance property of the superconductor this current persists, and thus the field due to this induced current repels the field due to the magnet. As a result, the magnet floats freely (i.e., levitated) above the superconductor.

Thus, the levitation of the magnet or maglev demonstrates two critical properties of superconductors: (i) zero resistance and (ii) Meissner effect.

Applications

Magnetically levitated vechiles are called maglev vehicles. The utility of such levitation in vechiles is that in the absence of contact between the moving and stationary systems, the friction is eliminated. With such an arrangement great speeds could be achieved with very low energy consumption.

(i) Maglev train

The levitation is based on two techniques: (i) Electromagnetic suspension (EMS) and (ii) Electrodynamic suspension (EDS).

In attractive EMS the electromagnets installed on the train bogies attract the iron rails (guideways). The vechile magnets wrap around the iron guideways and the attractive upward force lifts the train.

In EDS levitation is achived by creating a repulsive force between the train and guideways.

The basic idea of maglev train is to levitate it with magnetic fields so that there is no physical contact between the train and the rails (guideways). Consequently the maglev train can travel at very high speed. These trains travel at a speed of about 500 km/h.

(ii) A similar magnetic propulsion system is being used to launch the satellite into orbits directly from the earth without the use of rockets.

8.8.3 Other Applications of Superconductors

(1) Superconductors can be used to transmit electrical power over very long distances without any power loss or any voltage drop.

(2) Superconducting generators has the benefit of small size and low energy consumption than the conventional generators.

(3) Superconducting coils are used in N.M.R. (nuclear magnetic resonance) imaging equipments which are used in hospitals for scanning the whole body to diagnose medical problems.

(4) Very strong magnetic fields can be generated with coils made of high T_c superconducting materials.

(5) Superconductors can act as relay or switching system in a computer. They can also be used as a memory or storage element in computers.

Cryotron: It is a relay or switch made of superconductors whose size can be made very small. In addition, these switches consume very less current.

The cryotron consists of two superconducting materials A and B. Let the material A be inside the coil of wire B, as shown in Figure 8.11.

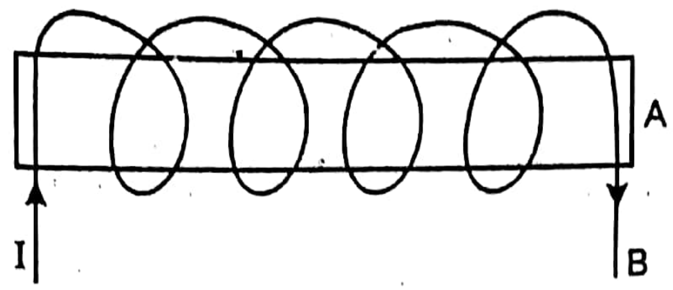

Figure 8.11: Cryotron

Let the critical field of the material A be H_{cA} and that of B be H_{cB}, respectively, and also let $H_{cA} < H_{cB}$. If a current I is passed through the material B, the current induces a magnetic field H. If this induced field H happens to be greater than H_{cA} then the superconducting property of the material A gets destroyed.

Hence the resistivity increases and the contact is broken. Thus, the current in A can be controlled by the current in B, and hence this system can act as a relay or switch element.

(6) Very fast and accurate computers can be constructed using superconductors and the power consumption is also very low.

(7) Ore separation can be done efficiently using superconducting magnets.