# 20

# Superconductivity

## Learning Objectives

*After reading this chapter you will be able to*

**LO 1** Gain knowledge/Learn about electrical resistivity of solids and phonons

**LO 2** Understand the properties and classification of superconductors

**LO 3** Learn about effect of magnetic field and Isotope effect on superconductivity

**LO 4** Know how London equations explain zero resistance and ideal diamagnetism of superconductors

**LO 5** Discuss penetration depth of supercurrent and magnetic flux in superconductors

**LO 6** Explain formation of Cooper pairs and its relation to Bose–Einstein condensation

**LO 7** Understand basis of BCS theory and coherence length

**LO 8** Analyse high temperature conductivity and applications of conductivity

## Introduction

The phenomenon of *superconductivity* was first discovered by Kammerlingh Onnes in 1911. He found that electrical resistivity of some metals, alloys and compounds drops suddenly to zero when they are cooled below a certain temperature. This phenomenon is known as *superconductivity* and the materials that exhibit this behaviour are called as *superconductors*. However, all the materials cannot superconduct even at 0 K. The temperature at which a normal material turns into a superconducting state is called critical temperature $T_c$. Each superconducting material has its own critical temperature. Kammerlingh Onnes discovered that the electrical resistance of highly purified mercury dropped abruptly to zero at 4.15 K, as shown in Fig. 20.1.

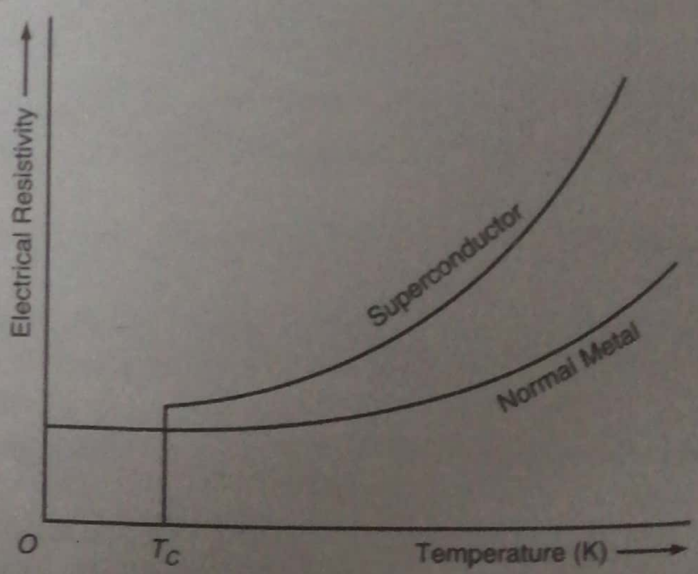


**Figure 20.1**

Generally good conductors like Au, Ag, Cu, Li, Na, K, etc. do not show superconductivity even at absolute zero.

The interaction of electrons with one another and with the lattice ions were averaged out by the free electron theory (model) approximation. This could be responsible for resistance to the flow of electrons under normal conditions. This independent particle model was unable to explain superconductivity. The clear understanding of the phenomenon of superconductivity requires the consideration of collective behavior of electrons and ions. This is called many body effects in solids.

## 20.1 ELECTRICAL RESISTIVITY OF SOLIDS AND PHONONS

LO1

There are several factors that contribute to the electrical resistivity of a solid. For example, the deviations from a perfect lattice, which may be due to impurities or structural defects in crystal, can scatter the electrons. Moreover, the vibrations of lattice ions take place in normal modes. These vibrations constitute acoustic waves which travel through the solid. These waves are called phonons, which carry momentum. It is obvious that the number of phonons will increase if the temperature is raised. In the presence of phonons, now there is an interaction between the electrons and phonons. This interaction scatters conduction electrons and hence causes more resistance. Therefore, it is clear that the electrical resistance of a solid will decrease if we cool the solid.

## 20.2 PROPERTIES OF SUPERCONDUCTORS

LO2

Electrical, magnetic and thermal properties are the main properties of the superconductors. These are described below.

### 20.2.1 Electrical Property

A superconductor is characterised by zero electrical resistivity. Once the current is started to flow, it will continue for years without any detectable decay (ideally) even if the applied voltage is removed.

### 20.2.2 Magnetic Property: Meissner Effect

An important property of the superconducting phase is the repulsion of magnetic flux lines from the bulk of superconductor. It is called *Meissner effect*. When a specimen is placed in a magnetic field, the magnetic flux lines pass through it (Fig. 20.2a). Now, if the temperature is decreased below the transition temperature ($T_c$), it expels all the magnetic flux lines from inside of the specimen (Fig.20.2b). Hence, we get

$$B = \mu_0(H + M) = 0 \quad \text{or} \quad M = -H$$

where $M$ is the intensity of magnetisation due to applied magnetic field $H$. By the definition of magnetic susceptibility

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

Since diamagnetic materials have negative magnetic susceptibility, the specimen becomes an 'ideal diamagnetic' in superconducting state.

If a specimen of superconductor is placed in a strong magnetic field, the specimen loses its property of superconductivity and becomes normal material as shown in Fig. 20.2.

## 20.3 CLASSIFICATION OF SUPERCONDUCTORS LO2

On the basis of magnetising behaviour, superconductors can be classified as type-I (or soft) and type-II (or hard) superconductors.

### 20.3.1 Type-I (Soft) Superconductor

This type of superconductor obeys complete Meissner effect. It expels all the magnetic field abruptly from the interior and becomes an 'ideal diamagnetic material'. Magnetisation produced in the superconductor remains in the direction opposite to the applied external magnetic field, as shown in Fig. 20.5a. At the critical magnetising field, the magnetisation decreases abruptly and the material becomes normal. For all the values of external magnetic field above the critical value, the magnetic flux lines penetrate completely inside the material.

### 20.3.2 Type-II (Hard) Superconductor

This type of superconductor loses magnetisation gradually rather than abruptly. From the Fig. 20.5b it is clear that at the magnetic field $H_{C1}$, the flux starts penetrating into the material until the upper critical field $H_{C2}$ is reached. Between the two critical magnetic fields $H_{C1}$ and $H_{C2}$, the material is said to be in a mixed state. Above the magnetic field $H_{C2}$, the material becomes normal conductor. Inspite of the fact that the magnetic flux lines penetrate inside the material in the mixed state, the electrical resistivity continues to be zero upto the magnetic field $H_{C2}$.

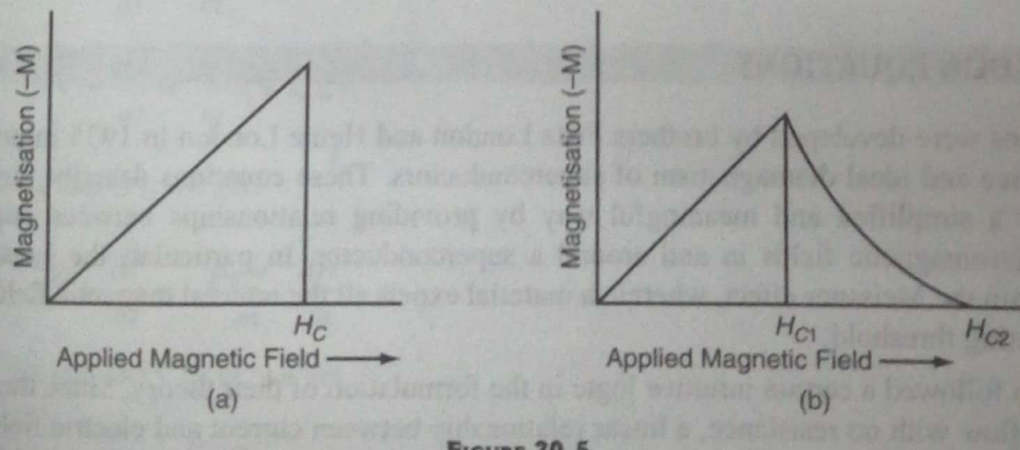


FIGURE 20.5

This curve demarcates the two states, i.e., it defines the boundary below which superconductivity is present and outside of which it behaves as a normal conductor.

## 20.5 ISOTOPE EFFECT

LO3

It has been observed that the critical temperature $T_c$ of superconductors varies with isotopic mass. Higher $T_c$ is found in samples with lighter nuclei. In mercury, $T_c$ varies form 4.85 K to 4.146 K as the average atomic mass $M$ varies from 199.5 a.m.u. to 203.4 a.m.u. It is also found that the transition temperature changes smoothly when we mix different isotopes of the same element. The dependence of $T_c$ on the atomic mass reveals that lattice vibrations and hence electron phonon interaction is deeply involved in the superconductivity. Based on experimental results it is found that

$$T_c \propto M^{-\alpha}$$

or

$$T_c M^{\alpha} = \text{Constant}$$

Here, $M$ is the atomic mass, $T_c$ is the critical temperature and $\alpha = 0.49 \pm 0.01$. In view of this value of $\alpha$ it was thought that $\alpha = 0.5$ is valid for most of the materials. With this we get

$$T_c M^{1/2} = \text{Constant}$$

or

$$T_{c_1} M_1^{1/2} = T_{c_2} M_2^{1/2}$$

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