CHAPTER 4

Superconductors

4.1 Introduction

Superconductivity was discovered by H. Kammerlingh Onnes in 1911. The first explanation for this superconductors is given by Bardeen Cooper and Schrieffer in 1957 and came to known as the BCS theory.

4.1.1 Superconductors

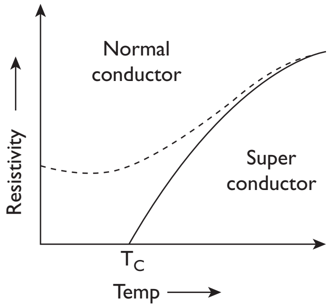
Superconductivity is the phenomenon by which certain materials conduct electricity without any resistance at low temperature and such a state of the material with zero electrical resistance is known as the superconducting state and the materials exhibiting this property are known as superconductors.

For example, the electrical resistance of pure mercury suddenly drops to zero, when it is cooled below 4.2 K and becomes a superconductor. This phenomenon of losing the resistivity absolutely, when cooled to sufficiently low temperature is called superconductivity.

4.1.2 Transition temperature (or) critical temperature

The temperature at which a normal conductor losses its resistivity and becomes a superconductor is known as transition temperature (or) critical temperature (T_C) as shown in Figure 4.1. For example, 4.2 K is the transition temperature for mercury.

Figure 4.1



(1) If the T_C is low, then the superconductors are known as low temperature superconductors.

(2) If the T_C is high, then is the superconductors are known as high temperature superconductors.

The superconducting transition is reversible (or) above the critical temperature, the superconductor becomes a normal conductor. Also, T_C is definite for any particular material.

4.2 Properties of superconductors

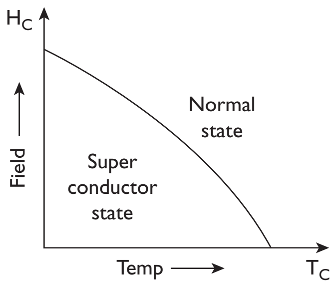
4.2.1 Electrical resistance

The electrical resistance of a superconducting material is very less and is of the order of 10^{-5} Ωm.

4.2.2 Magnetic property

When superconducting materials are subjected to very large value of magnetic field, the superconducting property is destroyed.

Figure 4.2



The field required to destroy the superconducting property is called critical magnetic field (H_C). It is given as

$$H_C = H_0\left[1 - \frac{T^2}{T_C^2}\right]$$

where H_0 is the critical field at 0 K and T_C is the transition temperature.

From the Figure 4.2, we can find that when the temperature of the material increases, the value of the critical magnetic field decreases. Hence the value of the critical field will be different for different materials.

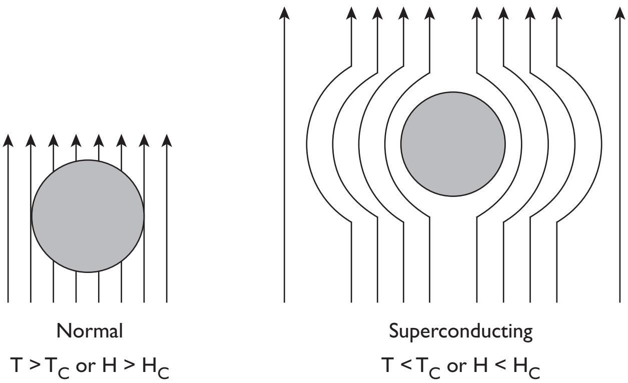
4.2.3 Effect of electric current

When a large value of ac current is applied to a superconducting material it induces some magnetic field in the material and because of this magnetic field the superconducting property of the material is destroyed.

4.2.4 Diamagnetic property—Meissner effect

When a superconducting material is placed in a magnetic field of flush density B the magnetic lines of force penetrates through the material as shown in Figure 4.3(a).

Figure 4.3(a) and (b)



Now when the material is cooled below its transition temperature when ($T \leq T_C$) then the magnetic lines of forces are expelled or ejected out from the material as shown in Figure 4.3(b).

We know that a diamagnetic material has the tendency to expel the magnetic lines of forces. Since the superconductors also expels the magnetic lines of forces it behaves as a perfect diamagnet. This behaviour was first observed by Meissner and hence called Meissner effect.

Meissner effect

When the superconducting material is placed in a magnetic field under the conduction when $T \leq T_C$ and $H \leq H_C$ the flux lines are excluded from the material. Thus the material exhibits perfect diamagnetism. This phenomenon is called Meissner effect.

Proof

We know that $B = \mu_o (H + I)$

When $B = 0$ we get $0 = \mu_o (H + I)$

Since $\mu_0 \neq 0; H + I = 0$

$-H = I$

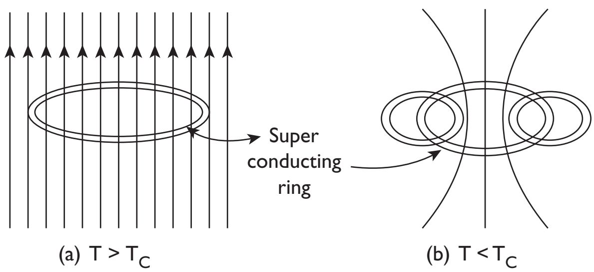
or $\frac{1}{H} = -I = x$

Since the susceptibility is negative, this shows that the superconductors is a perfect diamagnetic material.

4.2.5 Persistent current

When dc current of large magnitude is once induced in a superconducting ring then the current persists in the ring as shown in Figure 4.4 even after the removal of the field. This is known as persistent current.

Figure 4.4



This is due to the diamagnetic property (i.e.,) the magnetic flux inside the ring will be trapped in it and hence the current persists.

4.2.6 Thermal properties

The entropy and specific heat decreases at transition temperature. The thermal conductivity of a typical superconductor is low.

4.2.7 Isotope effect

The transition temperature varies due to the presence of isotopes.

Example: The atomic mass of mercury varies from 199.5 to 203.4 and hence the transition temperature varies from 4.185 K to 4.146 K. Due to the relationship

(i.e.,) $T_C \; \alpha \; \frac{1}{M^{\alpha}}$.

where M is atomic weight and α is constant ($\approx$0.5).

4.3 Types of superconductors

There are two types of superconductors based on their variation in magnetisation due to external magnetic field applied, viz.

(1) Type I superconductors (or) soft superconductors

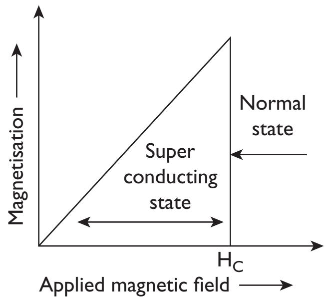
(2) Type II superconductors (or) hard superconductors

4.3.1 Type I superconductors

When the superconductors is kept in the magnetic field and if the field is increased the superconductor becomes a normal conductor abruptly at critical magnetic field as shown in Figure 4.5. These types of materials are termed as type I superconductors.

Below critical field, the specimen excludes all the magnetic lines of force and exhibit perfect Meissner effect. Hence type I superconductors are perfect diamagnets, represented by the negative sign in magnetisation (since for a diamagnet x is –ve).

Figure 4.5

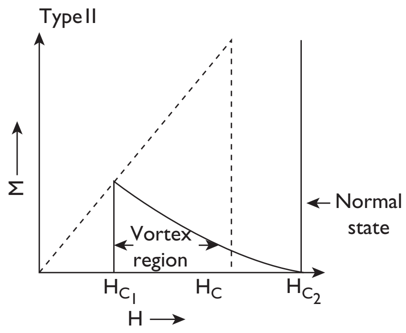


4.3.2 Type II superconductors

When the superconductor is kept in the magnetic field and if the field is increased, below the lower critical field H_C, then the material exhibits perfect diamagnetism (i.e.,) it behaves as a superconductor and above H_C, the magnetisation decreases and hence the magnetic flux starts penetrating through the material.

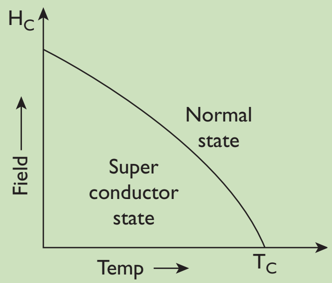
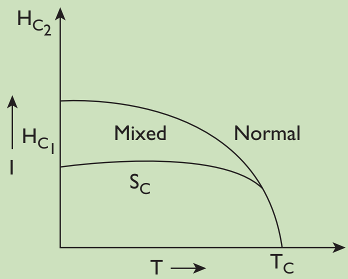
These specimens are said to be in a mixed state between H_{C_1} and H_{C_2}. Above H_{C_2} (upper critical field) it becomes a normal conductor as shown in Figure 4.6.

Figure 4.6



The material which loses its superconducting property gradually due to the increase in magnetic field is called type II superconductors.

Differences between type I and type II superconductors

S. No.	Type I	Type II
1.	The type I superconductors becomes a normal conductor abruptly at critical magnetic field.	Type II superconductors loses its superconducting property gradually due to increase in magnetic field.
2.	Here, we have only one critical field (H_C).	Here we have two critical fields, i.e., lower critical field (H_{C_1}) and upper critical field (H_{C_2}).
3.	No mixed state exists.	Mixed (or) vortex state is present.
4.	Highest known critical field is 0.1 tesla.	The critical field is greater than 30 tesla.
5.	Examples: Pl, Zn, Hg, Ga, Al, etc.	Examples: Vanadium, Niobium, etc.
6.	Magnetic phase diagram is 	Magnetic phase diagram is 

4.3.3 BCS theory [electron–lattice (phonons)–electron interaction]

In 1957, J. Bardeen, L.N. Cooper and J.R. Schrieffer developed the quantum theory of superconductivity, which came to be known as the BCS theory.

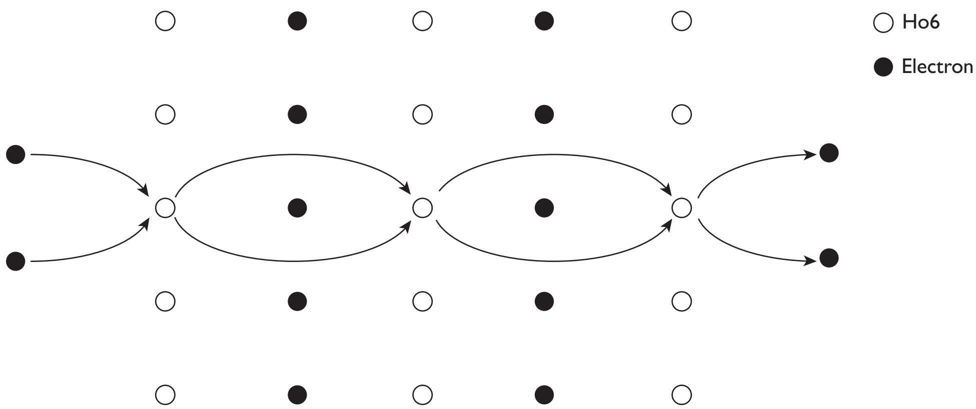
Starting from the two experimental results namely isotope effect and the variation of electronic specific heat with temperature, the BCS theory assumed interaction of two electrons through quanta of lattice vibrations. It successfully explained the effects like zero resistivity, Meissner effect, etc. The two principal features of the BCS theory are listed hereunder:

(1) Electrons form pairs called Cooper pairs which propagate through the lattice and

(2) Such propagation is without resistance because the electrons move in resonance with phonons.

To appreciate the formation of Cooper pairs, let us consider the model in Figure 4.7 in which two electrons propagate along a single lattice row. Each electron experiences an attraction towards its nearest positive ion. When the electrons get very close to each other in the region between ions, they repel each other due to Coulomb force. In an equilibrium condition, a balance between attraction and repulsion is established and the two electrons combine to form a Cooper pair. At normal temperatures the attractive force is too small and pairing of electron does not take place.

Figure 4.7



However, at lower temperatures, such pairing is energetically advantageous. In a typical superconductor the dense cloud of Cooper pairs form a collective state and the motion of all the Cooper pairs is correlated. As such the pairs drift cooperatively through the material. Thus the superconducting state is an ordered state of the conduction electrons since the density of Cooper pairs is very high even large currents require only a small velocity. The small velocity of ordered Cooper pairs minimise collision process and leads to zero resistivity. The electrons of a Cooper pair have a lower energy than two unpaired electrons.

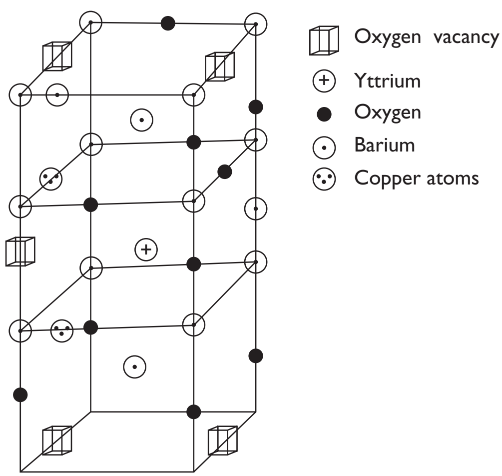
4.3.4 High temperature superconductors

Superconductors are divided into low T_C and high T_C superconductors based on their transition temperature. Broadly materials having T_C below 24 K are regarded as low T_C superconductors and those having T_C above 27 K are regarded as high T_C superconductors. However, in practice, materials for which liquid nitrogen cooling can cause transition to superconducting state may be regarded as high T_C superconductors. However, those require liquid helium coolant are considered as low T_C superconductors. The maximum transition that could be achieved before 1980s was 23.2 K in Nb_3, Ge, which is a metallic alloy. Therefore, it was hoped that metallic alloy systems could be made to have higher transition temperatures but such systems were not discovered. Therefore, the focus has shifted to ceramic oxides, which are insulating materials at normal temperatures.

In 1986 Muller discovered superconductivity in ceramic materials. He found that the mixed metallic oxide of lanthanum–barium–copper (La, $Ba_2Cu_3O_7$) exhibited superconductivity at about 30 K. The superconductivity of the oxide was linked with the deficiency of oxygen ions in the oxide compound when this deficiency of oxygen was carefully controlled, by keeping the sample in oxygen atmosphere, it was found that the material would exhibits superconductivity in the temperature range of 30 to 40 K.

In 1987 Chu and co-workers replaced lanthanum with yttrium and prepared $YBa_2Cu_3O_7$ with the transition temperature of 95 K. This was a major breakthrough, as this can be maintained in the superconducting state with far less expensive liquid nitrogen coolant (nitrogen exists in liquid state below 77 K) and marks the beginning of preparation of high T_C superconductors. This oxide also contains a deficiency of oxygen with the chemical formula $YBa_2Cu_3O_7$-d where d indicates the deficiency of oxygen and is in the range of 0 to 0.1. $YBa_2CU_3O_7$ is the most extensively studied high T_C superconductors and exhibits a defective perovskite structure with three perovskite cubic unit cells stacked on top of each other as shown in Figure 4.8.

Figure 4.8



Characteristics of HTS

(1) They have high transition temperature.

(2) They have perovskite crystal structure.

(3) They are reactive, brittle and cannot be easily formed (or) joined.

(4) They are oxides of copper in combination with other elements.

Applications of superconducting materials

Engineering applications

Based on their properties, they have the following applications:

(1) Since there is no loss in power (zero resistivity) superconductors can be used for the transmission of power over very large distances.

(2) Since the superconducting property can be easily destroyed it can be used in switching devices.

(3) Since the variation in small voltages cause large constant current it can be used in very sensitive electrical instruments. Ex: Galvanometer.

(4) Since the current in a superconducting ring can flow without any change in its value (persistent current), it can be used as mercury or storage element in computers.

(5) Since the size of the specimen can be reduced to about 10^{-4} cm, it can be used to manufacture electrical generators and transform in small sizes with high efficiency.

Apart from this they are also used to design cryotron, Josephson devices, SQUID, magnetic levitated trains (MAGLEV), modulators, rectifiers. etc.

4.3.5 CRYOTRON (magnetically operated current switch)

Principle

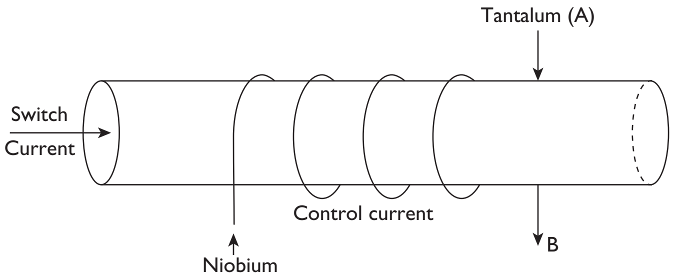
The superconducting property disappeared when the magnetic field is greater than the critical field (H_C).

Explanation

Let us consider a superconducting material ‘A’ surrounded by another superconducting material ‘B’ as shown in Figure 4.9.

Let the critical field $(H_C)_A$ of the material ‘A’ be less than the critical field $(H_C)_B$ of the material ‘B.’ Initially, let the temperature of the whole system be below the transition temperature of two materials (A and B).

Figure 4.9



Now, at operating temperature, the magnetic field produced by the material 'B' may exceed the critical field of 'A.' Hence the material 'A' becomes a normal conductor because the critical field of 'A' is less than the critical field of 'B.' Also 'B' will not become the normal conductor at the critical field of A because $H_{C_B} > H_{C_A}$.

Therefore the current in material 'A' can be controlled by the current in material 'B' and hence this system can act as a relay or switching elements.

4.3.6 Magnetic levitated train (MAGLEV)

Magnetic levitated train is the train which cannot move over the rail, rather it floats above the rail, under a particular condition, when it moves faster.

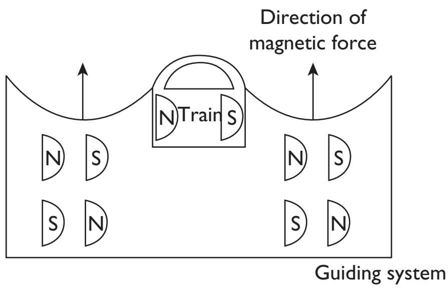
Principle

Electromagnetic induction is used as the principle (i.e.,) when there is a relative motion of a conductor across the magnetic field, current is induced in the conductor and vice versa.

Explanation

This train consists of superconducting magnets placed on each side of the train. The train can run in a guidance system which consists of a series of '8-' shaped coil as shown in Figure 4.10(a).

Figure 4.10(a)



Intially when the train starts, they slide on the rails. Now, when the train moves faster, the super conducting magnets on each side of the train will induce a current in the '8' shaped coils kept in the guidance system.

This induced current generates a magnetic fore in the coils in such a way that the lower half of the 8-shaped coils has the same magnetic poles as that of the superconducting magnet in the train, while the upper half has the opposite magnetic pole. Therefore, the total upward magnetic force acts on the train and hence the train is levitated (or) raised above the wheels (i.e.,) floats above the air.

Now, by alternatively changing the poles of the superconducting magnet in the train alternating currents can be induced in the '8' shaped coils. Thus, alternating series of north and south magnetic poles are produced in the coils, which pulls and pushes the super conducting magnets in the train is further moved.

4.3.7 SQUIDS

Superconducting Quantum Interference Devices are the improved model of Josephson devices. It has high efficiency, sensitivity and quick performance.

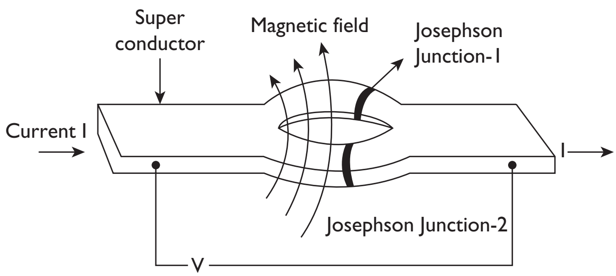
Principle

A small change in the magnetic field produces variation in the flux quantum.

Explanation

It consists of two identical Josephson junctions connected in parallel as shown in Figure 4.10(b). When the magnetic field is applied perpendicular to the plane of the ring, current is induced at the two Josephson junctions and produces interference pattern. The induced current flows around the ring, which corresponds to the value of magnetic field applied.

Figure 4.10(b) Josephson junctions



Therefore, SQUIDS are used to detect the variation in very minute magnetic signals. They are used as storage devices for magnetic flux.

They are also used in the study of earthquakes, removing paramagnetic impurities, detection of magnetic signals from the brain, etc.

Two Mark Questions and Answers

1. What is superconductivity?

   The phenomenon of losing the resistivity absolutely to zero, when cooled to sufficiently low temperature (i.e.,) below critical temperature (T_C) is called superconductivity.

2. What is critical temperature (or) transition temperature?

   The temperature at which a normal conductor loses its resistivity and becomes a superconductor is known as critical temperature.

3. Explain Meissner effect.

   When a superconducting material is kept in an external magnetic field under the condition when $T \leq T_C$ and $H \leq H_C$ the magnetic flux lines are completely excluded from the material and this phenomenon is known as Meissner effect.

4. Explain the term critical magnetic field in a superconductor.

   At any temperature, below the critical temperature a minimum magnetic field is required to destroy the superconducting property. This is known as critical magnetic field (H_C).

5. What is isotope effect in superconductivity?

   In superconducting materials, transition temperature varies with the average isotope mass M of its constituents.

$$T_C \;\alpha\; \frac{1}{M^{\alpha}}$$

$$T_C = \frac{\text{Const}}{M^{\alpha}} \qquad \therefore \quad M^{\alpha} T_C = \text{constant}$$

   where α is called the isotope effect coefficient

6. What are high temperature superconductors?

   High temperature superconductors are those which have high transition temperatures. This trend confirms that it might be possible to develop the superconductors at room temperature.

7. Give the differences between soft and hard superconductors.

S. No.	Soft superconductors	Hard superconductors
1.	The type I superconductors becomes a normal conductor abruptly at critical magnetic field.	Type II superconductors loses its superconducting property gradually due to increase in magnetic field.
2.	Here, we have only one critical field (H_C).	Here, we have two critical fields $\left(H_{C_1}\right)$ and $\left(H_{C_2}\right)$.
3.	No mixed state exists.	Mixed state present.

S. No.	Soft superconductors	Hard superconductors
4.	They have a low critical field.	They have a high critical field.
5.	Current flows through the surface only.	Current flows throughout the material.
6.	These can tolerate impurities without affecting their superconducting properties.	These cannot tolerate impurities (i.e.,), the impurities affect the superconducting property.
7.	Examples: Tin, aluminium, etc.	Examples: Tantalum, neobium, etc.

8. What are the properties of high T_C superconductors?

They have high transition temperatures. They have modified perovskite structure. Formation of superconducting state in high T_C superconductor is direction dependent.

9. What are type I superconductors?

The superconductors in which the magnetic field is totally excluded from the interior of superconductors below a certain magnetising field H_C and at H_C the material loses superconductivity abruptly and magnetic field penetrates fully are termed as type I superconductors.

10. What are type II superconductors?

When a superconductor is kept in an external magnetic field, and if the superconductor becomes a normal conductor gradually with respect to various critical magnetic fields, it is called a type II superconductor.

11. What is meant by persistent current?

When a dc current of large magnitude is once induced in a superconducting ring, then due to the diamagnetic property of the superconductor, the magnetic flux is trapped inside the ring and hence the current persist in the ring for a longer time. This current is called persistent current. Refer to Figure 4.4.

University Questions

PART A

1. Explain type I and type II superconductors.
2. On the basis of spin, classify ferro, antiferro and ferrimagnetic materials.
3. What is Meissner effect?
4. What is mean by hysteresis loss?
5. A magnetic field strength of 2×10^5 ampere s/m is applied to a paramagnetic material with a relative permeability of 1.01. Calculate the values of B and M.

6. What do you understand by the terms ‘critical temperature’ and ‘critical field’ in a superconductor?
7. Distinguish between soft and hard magnets.
8. Mention some important applications of ferrites.
9. What are high temperature superconductors? Give examples.
10. Distinguish between hard and soft magnetic materials.
11. Draw the typical hysteresis loops for soft and hard magnets.
12. Distinguish between type I and II superconductors.
13. State the applications of ferrites.
14. Magnetic field intensity of a paramagnetic material is 104 A/m. At room temperature, its susceptibility is 3.7×10^{-3}. Calculate the magnetisation in the material.
15. Write four applications of superconductivity.
16. What are the essential differences between hard and soft magnetic materials?
17. What does a Bohr magnetron represent? State its value.
18. The saturation value of magnetisation of iron is 1.75×10^{6} Am^{-1}. Iron has body centred cubic structure with an elementary cube edge of 2.86 A. Every unit cell has two atoms. Calculate the average number of Bohr magnetrons contributed to the magnetisation per atom.
19. What is Bohr magnetron? Obtain its value.
20. The superconducting transition temperature (T_C) for mercury with isotropic mass 199.5 is 418.5 K. Calculate the value of T_C when its mass changes to 203.4.
21. What is hysteresis? Draw hysteresis curve for a soft magnetic material.
22. What is one Bohr magnetron?
23. Define Meissner effect.
24. On what principle does the SQUID works?
25. What are ferrites? How are they superior to magnetic materials?
26. What is magnetic levitation?
27. Write the applications of ferrites.
28. What is Meissner effect?
29. What are the properties of ferromagnetic materials?
30. What are SQUIDS? What is their use?
31. What is pseudoelasticity in SMA?
32. Distinguish between para- and ferromagnetism.

PART B

1. Give an account of high T_C superconductors and their applications.
2. (i) Mention four important ferrites and their applications.
   (ii) What are reversible and irreversible domains? Based on that, explain the phenomenon of hysteresis in ferromagnetic materials.
   (iii) Define exchange energy and magnetostrictive energy.
3. (i) What is hysteresis?
   (ii) Draw a B–H curve for a ferromagnetic material and identify retentivity and coercive field on the curve.
   (iii) What is the energy loss per cycle and how it is used to choose materials for applications?
   (iv) What are ferrites? How they are superior to ferromagnetic materials?
4. (i) Give the differences between type I and type II superconductors.
   (ii) Briefly describe the Meissner effect.
   (iii) Give an account on the development of high temperature superconductors.
5. Explain the origin of ferromagnetism.
6. (i) Distinguish between soft and hard magnetic materials.
   (ii) Give an account of structure, properties and applications of ferrites.
7. What are Meissner's and isotope effects?
8. Explain ferromagnetic materials.
9. What is ferromagnetism? Explain how domain theory can be used to explain the magnetic behaviour of ferromagnetic materials.
10. (i) Explain Meissner effect and magnetic levitation.
    (ii) Discuss the application of superconductors.
11. Differentiate high T_C and low T_C superconductors.
12. Distinguish between dia, para, ferro and antiferro magnetic materials. Mention their properties and applications.
13. Explain the domain theory of ferromagnetism.
14. Using the concept of domains, explain the formation of hysteresis in ferromagnetic materials.
15. Discuss the properties and applications of superconductors.
16. Explain the domain theory of ferromagnetism. Using that explain the formation of hysteresis in ferromagnetic materials.
17. Give a note on the applications of superconductors.
18. Discuss in detail the different types of magnetic materials with a neat sketch and explain the magnetic hysteresis characteristics of ferromagnetic materials on the basis of domain theory.

19. Give an account on magnetic levitation by superconductors.
20. Explain four different types of ferrites along with their applications.
21. (i) How a superconducting state is distinguished from a normal state?
    (ii) When a metal changes from a normal state to a superconducting state which properties get changed and which does not?
    (iii) Explain Meissner effect.
22. (i) Differentiate between diamagnetic, paramagnetic and ferromagnetic substance on the basis of susceptibility.
    (ii) What is a magnetic domain?
    (iii) What are its characteristics?
23. Discuss the properties and applications of superconductors.
24. Discuss the different components of ferromagnetic energy.
25. Discuss antiferromagnetic materials.
26. (i) Explain type I and type II superconductors.
    (ii) Discuss briefly the BC theory of superconductors.
27. (i) Discuss high T_C superconductors.
    (ii) Discuss the structure and properties of $YBa_2Cu_3O_{7-8}$ superconductors.
28. What are the limitations of high T_C superconductors?
29. (i) What are superconductors?
    (ii) Mention the important property changes that occur in materials when they change from a normal to a superconducting state.
    (iii) What is Meissner effect?
    (iv) What are type I and type II superconductors?
    (v) Mention three applications of superconductors.
30. (i) Classify the magnetic materials on the basis of spin.
    (ii) What are ferromagnetic domains?
    (iii) How the existence of domains is explained?
    (iv) Draw a D–H curve and identify retentivity and coercive field.
31. What are ferromagnetic materials?
32. (i) Explain superconducting phenomena. What are its properties?
    (ii) Distinguish between type I and type II superconductors.
33. Superconducting tin has a critical temperature of 3.7 K at ferromagnetic field and critical field of 0.0306 testla at 0 K. Find their critical field at 2 K.
34. (i) Give the classification of magnetic materials and explain their properties.
    (ii) Distinguish between hard and soft magnetic materials.
35. Discuss the structure of ferrite and describe its preparation.
36. Describe the structure of ferrites. Mention its applications.