3.7. SUPERCONDUCTING MATERIALS

3.7.1. INTRODUCTION

When a material is cooled to a sufficiently low temperature, it loses its electirical resistance suddenly. This phenomenon is known as superconductivity. The temperature at which the transition occurs from normal state to superconducting state is known as **transition temperature (T_c)**. Below T_c the material is in the superconducting state and above T_c the material is in the normal state. Materials exhibiting this property are known as superconductors.

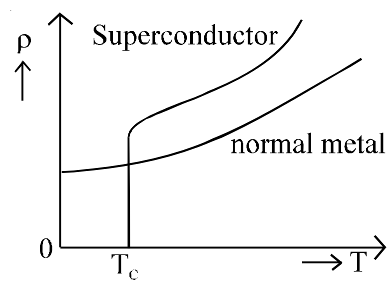


Fig. 3.27 Superconductivity

3.8. PROPERTIES OF SUPERCONDUCTORS:

1. Zero electrical resistance:

Experiments carried out by Collins showed that the value of the d.c current induced in the superconducting ring was not changed for more than a year and he observed the ratio $(R_s/R_n) < 10^{-5}$ where R_s is the resistance of the material in the superconducting state and R_n is the resistance of the same material in the normal state.

2. Effect of magnetic field :

The superconducting property of a material can be destroyed by the application of a strong magnetic field. At any termperature, the minimum field required to destroy the superconducting property is called critical field (H_c) of the material.

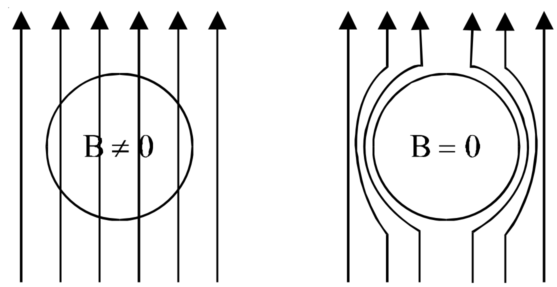
$$H_C = H_0 \left[1 - \frac{T^2}{T_C^2}\right]$$

where, H_0 - critical field at 0K

T_C - Transition temperature

3. Diamagnetic property (Meissner effect) :

When a material in the normal state is placed in the magnetic field, the lines of force penetrate through the material. If the temperature of the material is reduced below the transition temperature (T_c), the magnetic lines of force are expelled from the material. A diamagnetic material also repels the magnetic lines of force. Therefore a superconducting material behaves as a perfect diamagnetic material. This behaviour was first observed by Meissner and hence this effect is named as Meissner effect.



(a) Normal state (b) superconducting state

Fig. 3.28 Meissner effect

4. Effect of electric current :

Flow of large amount of electric current through a superconducting material destroys the superconducting property. The current flowing through a coil will set up a magnetic field. If the strength of the induced magnetic field exceeds the critical field H_C, the superconducting property will be destroyed.

5. Effect of pressure :

The transistion temperature of a material increases with pressure. Research works are in progress to get room temperature superconductors by applying high pressure.

6. Isotope effect :

The presence of isotopes slightly modifies the transition temperature of a material. The transition temperature is inversely proportional to the square root of the atomic mass of the isotope.

$$T_c m^{1/2} = \text{constant}$$

3.9. TYPES OF SUPERCONDUCTORS

Superconductors are classified into two groups based on their magnetic behaviour.

3.9.1. Type-I (Soft) Superconductors

The type-1 superconductors behave as perfect diamagnets and the Meissner effect is complete in these materials. The magnetisation curve for type-I superconductors is shown in figure 2.15. When the external magnetic field is equal to the critical field Hc, the material loses its superconducting property abruptly and the magnetic lines of force completely penetrate through it. Thus in type-I superconductors the Meissner effect is complete.

The critical field for these superconductors is less and is of the order of 0.1 Tesla. Hence they are named as soft superconductors and are not suitable for high field applications. e.g., lead, tin, mercury, zinc etc.,

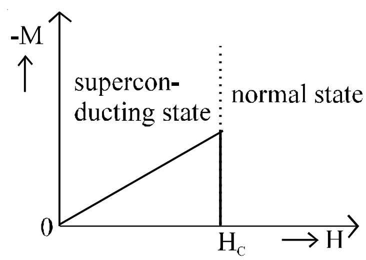


Fig 2.15 Magnetisation curve for type - I superconductor

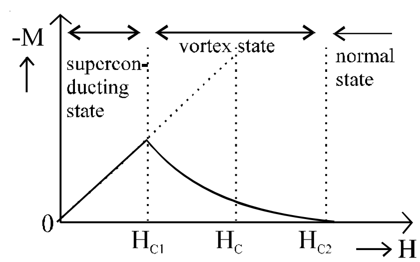


Fig 2.16 Magnetisation curve for type - II superconductor

3.9.2. Type-II (Hard) Superconductors

Type-II superconductors are not perfect diamagnets and the Meissner effect is incomplete in these materials. The magnetisation curve for type-II superconductors is shown in figure 2.16. These materials posses two critical fields H_{C1} and H_{C2}. Below the lower critical field H_{C1}, the material is a perfect superconductor and the magnetic lines of force are completely expelled from the material. Above the upper critical field H_{C2} the material is in the normal state and the lines of force are completely penetrating through the material. In between H_{C1} and H_{C2} the material is in the vortex state (mixed state). At H_{C1} the penetration of lines of force starts and at H_{C2} the penetration completes. Thus in type-II superconductors the Meissner effect is incomplete.

The value of the critical field H_{C2} for type-II superconductors is about 100 times greater than the critical field value of type-I superconductors. Hence they are named as hard superconductors and are suitable for high field applications. e.g., zirconium, niobium, etc.

3.9.3. Differences between type I and type II super conductors

S.No.	Type I (Soft) Superconductor	Type II (Hard) Superconductor
1.	Type I superconductor becomes a normal conductor abruptly at criticial magnetic field.	Type II superconductor 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. (Lower critical field (H_{c1}) and Upper critical field (H_{c2}))
3.	Meissner effect is complete	Meissner effect is incomplete.
4.	No mixed state exists	Mixed (or) Vortex state is present.
5.	The critical field is low (0.1 Tesla)	The critical field is greater than Type I superconductors (upto 30 Teslas).

3.10. BCS Theory of Superconductivity

Bardeen Gooper and Schriffer's theory is the first theory that explain the phenomenon of superconductivity. There are two consequence of BCS Theory. They are

(i) Cooper Pair

(ii) Electron - Electron and Electron - Lattice interactions.

(i) Copper Pair:

According to Coloumb's theory, me know that two electrons will repell with each other. But for some times the two negatively charged electrons will attract with each other. Let us consider two electrons e_1 and e_2. Among the two electrons, one electron may attract possitive ions towards itself. So a +ive ion screening is formed around the electron 1 or electron 2.This the ion screening is called **'Phonon cloud'**. The chage of the Phonon cloud is possitive. So sometimes it may produce a net possitive charge over the electron 1 or 2. At this time two electrons will attract with each other. Cooper showed that these two electrons are paired to form a single system and their motions are corelative over the lattice. They move over the lattice points to a certain small distance called **Coherence length**. It is of the order of 10^{-6}m.

(ii) Electron - Lattice and Electron - Electron Interactions;

When the temperature of the superconducting material is less than its critical temperature, the electron - Lattice interaction is Stronger than Electron - Electron interaction (ie) There is strong repulsine force is acting between the electron and the lattice points. So the cooper pairs will have a property. They will smoothly sailing over the lattice points with out any collision with the lattice points. So there is no collission between electron & electron and also between electron & lattice points. There is no restriction offered to the flow of free lectrons. So the resistivity is zero so the materials act as a superconductivity.

3.11. HIGH TEMPERATURE SUPERCONDUCTORS

High temperature superconductors are the materials which have transition temperature T_c > 100K. Usually in high temperature superconductors, the charge carriers are holes. Hence they are named as p-type superconductors.

Examples:

1) $BaPb_{0.75}Bi_{0.25}O_3$[BPBO} has the transitiation temperature T_c=12K
2) $La_{1.85}Ba_{0.15}CuO_4$ [LBCO] has the transition temperature T_c=36K
3) $YBa_2Cu_3O_7$ [YBCO] has the transition temperature T_c=90K
4) $Tl_2Ba_2Ca_2Cu_3O_{10}$[TBCO] has the transition temperature T_c=120K

3.11.1. Characteristics of High Temperature Superconductors

1) The transition temperature is high.
2) They are referred to as 1-2-3 compound
3) They have pervoskite crystal structure.
4) They are direction dependent.
5) They are reactive, brittle and cannot be easily formed (or) joined.
6) They are oxides of copper in combination with other elements.

3.11.2. Crystal structure of $YBa_2Cu_3O_7$

Preparation : $YBa_2Cu_3O_7$ is prepared by heating Y_2O_3, $BaCO_3$ and CuO in the atomic ratio 1:2:3 at a very high temperature say 1100^0C. Here $BaCO_3$ decomposes to give BaO and CO_2, giving rise to the pervoskite crystal structure as shown in figure 3.31.

It is found that the defect free $YBa_2\,Cu_3O_9$ is not a superconductor. But the material with oxygen defect modification of the pervoskite structure $YBa_2Cu_3O_7$ is a superconductor. In $YBa_2Cu_3O_7$ about one third of the oxygen positions are vacant. Therefore we can say, that the oxygen defect induces superconductivity in persovskite structure.

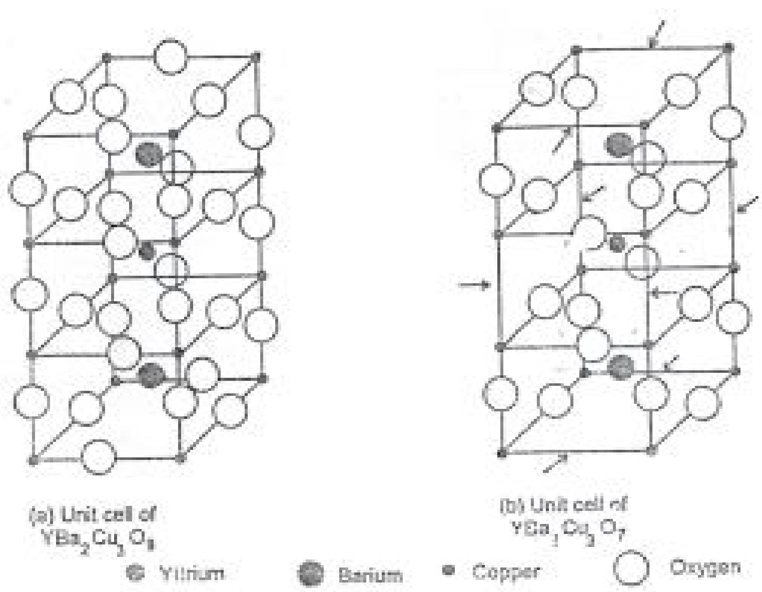


Fig 3.31 Pervoskite ordinary and superconducting structures

3.12. APPLICATIONS OF SUPERCONDUCTORS :

1. Superconducting solenoids :

Superconducting solenoids are useful in magneto-hydrodynamic power conversion and in other engineering areas.

2. Electric motors and generators :

Electrical machines, generators and motors with superconductor wirings are small in size with high efficiency.

3. Lossless power transmission :

Electrical power transmission lines with superconducting cables can transmit high power to any distance without loss.

4. Magnetic ore separation :

High efficient magnetic ore separating machines can be built using superconductors.

5. Memory storage :

Since the current in a superconducting ring can flow for a longer time without change, it can be used as a memory storage element in computers.

6. Cryotron

It is a magnetically operated current switch.

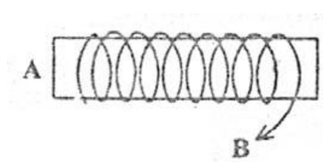


Fig 3.32 Cryotron

Principle : The superconducting property disappears when the magnetic field is greater thatn critical field (H_e).

Let us consider a superconducting material 'A' surrounded by another superconducting material 'B' as shown in figure 3.32.

Let the critical field of the material A be Less than the critical field of the material 'B'. Initially, let the temperature of the whole system be below the transition temperature of the two materials (A and B).

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

Therefore the current in material 'A' can be controleld by the current in material 'B' and hence this system can act as a Relay (or) Switching elements.

7. Josephson devices

The Josephson junction consists of a thin layer of insulating material placed in between two superconducting material (1 and 2) as shown in figure 3.33. Here the insulator acts as a barrier to the flow of conduction electrons from one superconductor to the other .

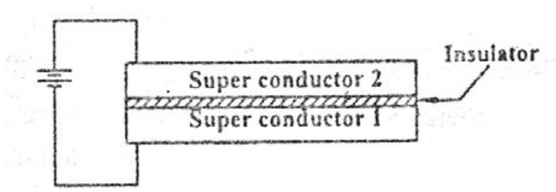


Fig 3.33 Josephson Junction

If a d.c. voltage 'V' is applied across the superconductors, then oscillating current starts flowing between the superconductors by tunneling effect. (i.e.,) Due to the increase in voltages, more and more thermally excited electrons in the superconductor 1 will tunnel across the insulator into the superconductor 2 and hence the current increases. The current has two components viz.

i) d.c. Component : This current component persists even after the external voltage is cutoff.

D.C. Josephson Effect

The flow of d.c. current across the junction of two superconductors separated by a thin insulator layer in the absence of any external electric field is called D.C. Josephson effect

ii) a.c. Component: This current component persists only upto which the external voltage is applied. The frequency of oscillating current is

$$\mu = \frac{2eV}{h}$$

A.C. Josephson Effect

A d.c. voltage applied across the junctions of two superconductors separated by a thin insulator layer causes R.F current oscillations across the junction with frequency $\mu = \frac{2eV}{h}$ is called A.C. Josephson Effect.

Josephson devices are used to produce microwaves, calibration of voltmeters etc.

8. SQUIDS

SQUIDS stands for **Superconducting Quantum Interference Device.** It is the improved model of Josephson devices. It has high efficiency, sensitivity and quick performance.

It consists of a superconducting ring which can have magnetic fields of quantum values (1,2,3......).

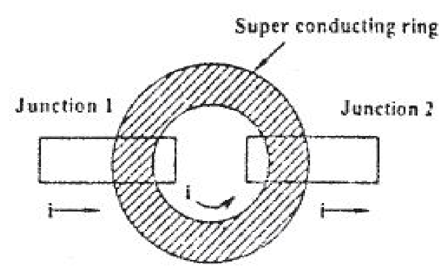


Fig 3.34 SQUID

Two Josephson junctions are mounted on the ring as shown in figure 2.20. 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 induceed current flows around the ring so that the magnetic flux in the ring can have quantum values, which corresponds to the value of the magnetic field applied.

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

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

9. Magnetic Levitation

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

Principle: Electro-magnetic 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 super conducting magnets placed on each side of the train. The train can run in a guidance system which consists of a series of “8” shaped coils as shown in fig. 3.35

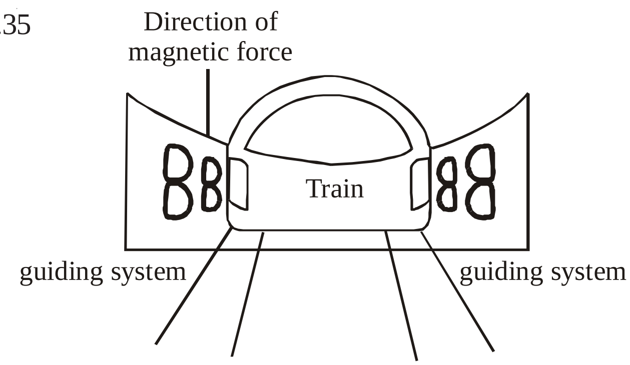


Fig. 3.35

Initially when the train starts, they slide on the rails. Now, when train moves faster, the super conducting magnets on each side of the train will induce a current in the 8shaped coils kept in the guidance systems.This induced current generates a magnetic force in the coils in such a way that the lower half of the 8-shaped coil has the same magnetic pole as that of the super-conducting 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) rised above the wheels (i.e.,) the train now floats above the air.

Now, by alternatively changing the poles of the super-conducting 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 and hence the train is further moved. This magnetic levitated train can travel a speed of 500-km/hour -double the speed of existing fastest train.

Part A Questions and Answers

1. *Show that* $\chi_m = \mu_{r-1}$

We have the realtion connecting B, H, M, μ and μ_0 as,

$$B = \mu H = \mu_0(M + H)$$

Substituting for $\mu = \mu_0\mu_r$, we get,

Dividing both sides by $\mu_0 H$

$$\mu_r = 1 + \frac{M}{H}$$

$$= 1 + \chi_m$$

$$\therefore \chi_m = \mu_r - 1 \qquad \text{Hence Proved.}$$

2. *Prove that* χ_m ***is negative for a diamagnetic material***

We have,

Magnetic induction, $B = \mu_0(M + H)$

The magnetic induction inside a diamagnetic material is zero.

$$\text{i.e., } \mu_0(M + H) = 0$$

$$\text{or } M = -H$$

$$\therefore \text{The susceptibility, } \chi_m = \frac{M}{H} = -1$$

Thus the magnetic susceptibility of a diamagnetic material is negative.

3. *What are diamagnetic materials? What are their properties? Give two examples*

Materials which get weak magnetisaiton in a direction opposite to that of the applied field are called diamagnetic materials.

e.g., cadmium, gold, silver etc.

Properties :

(i) They possess no permanent dipole moment

(ii) The magnetic susceptibility is small and negative. The magnetic susceptibility is a constant and independent of temperature.

4. *What are Ferromagnetic materials? What are their properties? Give two examples.*

Materials which possess permanent dipoles and exhibit spontaneous magnetisation are called ferromagnetic materials, e.g., silicon steel, nickel steel, etc.,

Properties:

1. They strongly attract the lines of force.
2. Dipoles in a domain align parallel to one another and there is a net magnetic moment in a domain. But the domains are aligned randomly and the resulting magnetic moment is zero.
3. The magnetic susceptibility is large and positive. It decreases when the temperature increases.
4. When the temperature of a ferromagnetic material is increased, the ferromagnetism disappears at a critical temperature. This temperature is called Curie temperature.

5. *What are ferrites? Give examples?*

In some ceramic materials, different ions have different magnitudes for their magnetic moments. When these magnetic moments are aligned antiparallel to each other, there is a net magnetic moment in one direction. This group of ceramic ferrimagnetic materials are called ferrites. They have domain structure and hysteresis loops similar to those of ferromagnetic materials.

e.g., yttrium iron garnet, barium ferrite.

6. Define magnetic hysteresis and hysteresis loss.

When ferromagnetic materials like Fe, Co and Ni are taken through a cycle of magnetising field, magnetic induction lags behind the field. This lagging of magnetic induction behind the field is magnetic hysteresis.

Due to hysteresis some amount of energy is dissipated in the form of heat enegy. This dissipation in energy per unit volume of the material is called hysteresis loss. This loss is directly proportional to the area of the loop.

7. Define energy product : What is the significance of energy product?

The energy product of a hard magnetic material is the area of the largest B-H rectangle drawn on the second quadrant of the hysteresis curve. The value of the energy product refers the enregy required to damagnetise a permanent magnet. If the energy product is very high, the material is a strong permanent magnet. (fig 4.16)

8. What may be the shape of the hysteresis curves preferred for memory devices?

Rectangular

9. Distinguish between soft and hard magnetic materials:

	Soft magnetic materials	Hard magnetic materials
1.	They can be easily magnetised and damagnetised	1. It is difficult to magnetise and demagnetise them
2.	The permeability is high	2. Permeability is low
3.	Hysteresis loop is steep.Energy stored is small	3. Hyteresis loop is wide and high. Energy stored is large
4.	Hysteresis loss is small	4. Hysteresis loss is large
5.	Eddy current loss is small	5. Eddy current loss is large
6.	Temperary Magnets. (cast iron, nickel, steel etc.)	6. Permanent magnets (alnico alloys, rare earth alloys etc.)

10. Distinguish between ferro and ferrimagnetic materials:

	Ferromagnetic materials	Ferrimagnetic materials
1.	The magnetic dipoles are aligned parallel to each other in a particular domain	Dipoles with different magnitude aligned antiparallel to each other in a particular domain.
2.	The saturation magnetisation is very high.	The saturation magnetisation is not high compared to ferromagnetic materials.
3.	They are not electrical insulators. e.g., Cast iron, alnico alloys etc.	Soft ferrites are electrical insulators. e.g., Magnesium ferrite, Barium ferrite.

11. Define anisotropic energy? What are easy and hard axes of a magnetic crystal?

Anisotropy energy : Magnetisation is an anisotropic property in crystals. The crystal anisotropic energy is the energy of magnetisation which is a function of crystal orientation. The anisotropic energy is very important in determining the character of domain boundary.

Easy axis : The crystal is easily magnetised if the field is applied in this direction.

Hard axis: Magnetising the crystal is very hard if the field is applied in this direction.

12. What are reversible and irreversible domains?

If a ferromagnetic material is subjected to a small external field the domain wall is slightly displaced away from the minimum energy. Whenever the field is removed, the domain wall returns to the original position. This gives a reversible domain wall movement and the domain is called the reversible domain.

In larger external field, the domain wall may be shifted to a more distant position where the energy curve has passed through a maximum and then diminished. On removing the field, the domain wall cannot cross the energy maximum and so it is unable to return to its initial position. This gives an irreversible domain wall movement and the domain is called the irreversible domain.

13. What are the general formula for soft and hard ferrites? What are their crystal structures?

Soft Ferrites : The general formula is MO. Fe_2O_3

Where, M-is a divalent metal ion.

They possess spinel and inverse spinel (cubic) structures.

Hard Ferrits : The general formula is $MO\ 6Fe_2O_3$

Where, M-is a divalent metal ion.

They possess hexagonal structure.

14. What is a magnetic bubble? What are their advantages?

The cylindrical domains of opposite polarity in the sea of positive magnetisation of a platelet are called magnetic bubbles.

1. The bubble memories can be moved from point to point at high speed.
2. The read out time/storing time is too smaller.
3. They are cheaper than core memories.

15. Compare magnetic disc and tape:

Magnetic Disc	Magnetic tape
1. Operating speed is high	1. Operating speed is small
2. Provide large storage capabilities	2. Provide large storage capabilities
3. Cannot be repeatedly used	3. Repeatedly used.
4. Costlier than tape	4. Cheaper than disc.

16 What is transition temperature?

The temperature at which a normal material turns into a superconductor is called transition temperature.

17.Explain the term critical magnetic field in superconductor.

At any temperature, below the critical temperature minimum magnetic field is required to destroy the super conducting property. This is known critical magnetic field

$(H_c) = Ho\ [1-(T / Tc)^{1/2}]$

Ho- critical magnetic field at absolute zero temp.

(H_c)- critical magnetic field at any temp.

Tc –transition temperature.

18.What is Meissner effect?

When a material is cooled below its transition temperature i.e., $T<T_C$ the material becomes a perfect diamagnet. The magnetic flux originally present in the material gets ejected out of a superconductor. This effect is known as Meissner effect.

19. What is isotope effect in superconductivity?)

In a super conducting materials, transition temperature varies with the average isotopic mass M of its constituents.

$$Tc \propto 1/M^{\propto}$$

Tc $M^{\propto}$ =constant where $\propto$ is called the isotope effect coefficient.

20. What are type -1 superconductors?

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

21. What are types - II superconductors?

The superconductors in which the material loses magnetisation gradually rather than suddenly are termed as type II superconductors

22. List the differences between type I and type II superconductors.

	Type I (Soft) Superconductor	**Type II (Hard) Superconductor**
1.	Type I superconductor becomes a normal conductor abruptly at criticial magnetic field.	Type II superconductor 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. (Lower critical field (H_{c1}) and Upper critical field (H_{c2})
3.	Meissner effect is complete	Meissner effect is incomplete.

23. What are high T_c superconductors? Give an example.

Any superconductor, if transition temperature is above 10 K is called high T_c superconductor.Example: $YBa_2Cu_30_7$

24. What are the properties of High T_c superconductors?

- They have high transition temperature,
- They have modified pervoskite structure.
- Formation of super conducting state in high Tc superconductors is direction dependent.
- They are oxides of copper in combination with other elements.

25. What are the applications of superconductors?

- Superconductors are used for the production of high magnetic field magnets.
- By using super conducting materials, it is possible to manufacture electrical generators and transformers in exceptionally small sizes having efficiency of 99.90%
- Super conducting materials are used in the construction of very sensitive electrical measuring instruments such as galvanometers.
- Super conducting materials if used for power cables will enable transmission of power over very long distances without any significant power loss or drop in voltage.

26. list the differences between type I and type II superconductors.

	Type I	**Type II**
1	The material loses magnetisation suddenly.	The material loses magnetisation gradually,
2	They exhibit complete Meissner effect i.e.,	They do not exhibit complete Meissner effect.
3	There is only one critical magnetic field (H_c).	There are two critical magnetic fields i.e., lower critical field (H_c; and upper critical fiek (H^c).
4	No mixed state exists.	Mixed state is present.

27. What is magnetic levitation?

The magnetic levitation is based on diamagnetic property of a superconductor -which is the rejection of magnetic flux lines. A superconductor can be suspended in air against the repulsive force from a permanent magnet. This magnetic levitation effect can be used for high-speed transportation without frictional loss.

28. What is SQUID?

SQUID is the acronym for Super conducting Quantum Interference Device; It is a double junction quantum interferometer. Two Josephson junctions mounted on a super conducting ring forms this interferometer. Squids are based on the flux quantization in a super-conducting ring. The total magnetic flux passing through the ring is quantized. It is an ultra-sensitive measuring instrument used detection of very weak magnetic field in the order 10^{-14} tesla

DESCRIPTIVE QUESTIONS

1. What are the different types of magnetic materials and their properties? Give examples for each case.
2. What are soft and hard ferromagnetic materials?. Distinguish between them. What are the applications of soft and hard ferromagnetic materials?
3. What is Ferrite Core Memory ? Explain in detail about Ferite Core Memory devices?
4. Discuss the (i) Domain theory of ferromagnetism.

   (ii). In what way the domain theory is successful?. Discuss the experimental evidence for the existence of domain structure.
5. What are ferrites? What are the types of ferrites? Discuss the crystal structure of the soft ferrites. What are the applications of soft and hard ferrites?
6. Discuss how data are stored by magnetic recording. Write a note on magnetic tape and magnetic disc. What are their advantages and disadvantages?
7. Describe high temperature superconductors with examples?
8. Distinguish between type I & Type II semiconductors?
9. Explain the BCS theory of super conductivity.
10. Whar are the applications of superconductors?