UNIT 4

MATERIALS BEHIND STORAGE APPLICATIONS

4. INTRODUCTION

Magnetism was observed as early as 800 B.C is naturally occurring material called load stone. In the modern concept, all materials, viz., metals, semiconductors and insulators are said to exhibit magnetism of different nature. The magnetic properties of solids originate in the motion of electrons and in the permanent magnetic moments of the atoms and electrons. 'Any material that can be magnetized by application of external magnetic field is called a magnetic material'. Of many types of magnetic materials diamagnetic, paramagnetic, ferromagnetic, anti-ferromagnetic and ferri-magnetic are the most important from the point of view of practical (Engineering) applications.

BASIC DEFINITIONS

We will first consider the terms and definitions used in magnetism.

i) Magnetic lines of force

These are the lines which are due to the magnetizing field and exist in air even when there is no magnetic substance in the field. It is shown in fig 3.1.

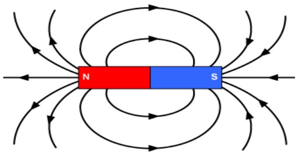


Fig.4.1 Magnetic lines of force

ii) Lines of magnetisation

If a magnetic substance is kept in a magnetic field, it is magnetised by induction and these lines of force passing within the substance due to magnetisation are known as lines of magnetisation as shown in fig.3.2.

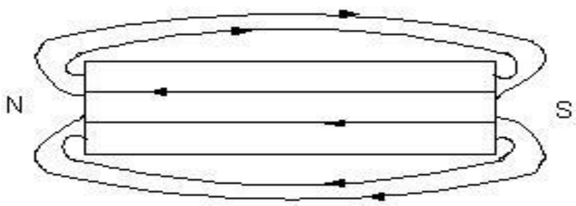


Fig.4.2 Lines of magnetisation

iii) Magnetic Induction or magnetic flux density (B)

In any material is number of lines of magnetic force passing through unit area perpendicularly (μ/A). Its unit is wbm^{-2} or Tesla.

iv)Magnetic field intensity (H)

At any point in the magnetic field is the force experienced by an unit north pole placed at that point. Its unit is Am^{-1}.

v) Magnetic Susceptibility (χ_m)

It is defined as the ratio between intensity of magnetization (I) and the magnetic field intensity (H).

$$\chi_m = \frac{I}{H}$$

vi) Intensity of Magnetization (I)

It is defined as the magnetic moment per unit volume.

Its unit is Am^{-1}.

$$I = \frac{M}{V}$$

vii) Magnetic permeability (μ)

It is defined as the ratio between the magnetic flux density (B) and the magnetic field intensity (H). It is the measure of degree at which the lines of force can penetrate through the material .Its unit is Hm^{-1}

$$\mu = \mu_o \mu_r = \frac{B}{H}$$

viii) Relative Permeability (μ_r)

It is the ratio between the permeability of the medium to the permeability of free space.

$$\mu_r = \frac{\mu}{\mu_o}$$

ix) Relation between (μ_r and χ_m)

When a magnetic material is placed in a magnetic field (H), then two types of lines of induction passes through the material viz

i) Due to magnetizing field (H)

ii) Due to material itself being magnetized by induction (I)

$\therefore$ Total flux density, $B = \mu_o(H + I)$ (1)

We know, $\mu = \frac{B}{H} \Longrightarrow B = \mu H$ (2)

Equating eqn (1) and (2) We get

$$\mu H = \mu_0 (H + I)$$

Since $\mu = \mu_0 \mu_r$ we have

$$\mu_0 \mu_r H = \mu_0 H \left[1 + \frac{I}{H}\right]$$

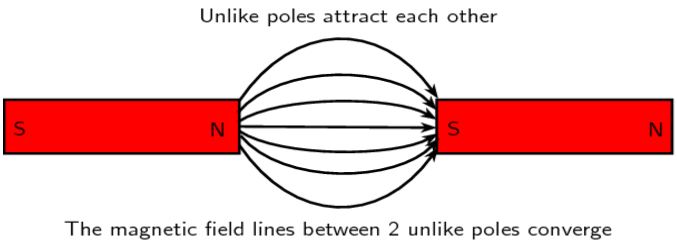
Here, $\dfrac{I}{H} = \chi_m$

$$\mu_r = \left[1 + \frac{I}{H}\right] = 1 + x_m$$

$$\frac{I}{H} = x_m$$

x) Force between two poles

Let us consider two poles of pole strength m_1 and m_2 placed at a distance 'r' apart as shown in fig.



Force between two poles

From the coulomb's law of forces, the force of attraction (or) repulsion between the isolated point magnetic poles is proportional to the product of pole strengths and is inversely proportional to the square of the distance between them

i.e, $F \propto \dfrac{m_1 m_2}{r^2}$

$$F = K \frac{m_1 m_2}{r^2}$$

In terms of unit vector $\hat{r}$ directed from m_1 to m_2

$$F = k \frac{m_1 m_2}{r^2} \hat{r}$$

$$\vec{F} = K \frac{m_1 m_2}{r^3} \vec{r} \qquad \hat{r} = \frac{\vec{r}}{r}$$

Here K is a constant of proportionality

$$K = \frac{1}{4\pi \mu_0 \mu_r}$$

Where $\mu_0 \rightarrow$ Permeability in free space $\left(4\pi \times 10^{-7} H/M\right)$

$\mu_r \rightarrow$ Relative permeability

$$\vec{F} = \frac{m_1 m_2}{4\pi\mu_0\mu_r r^3}\vec{r} \text{ for air } \mu_r = 1$$

$$\therefore \vec{F} = \frac{m_1 m_2}{4\pi\mu_0 r^3}\vec{r} \text{ Newton}$$

Origin of Magnetic Moment – Bohr Magneton

We shall now discuss now what contribute to the permanent magnetic dipole moment of the atomic constituents of matter. Whenever a charged particle has an angular momentum, it contributes to the permanent dipole moment. In general, these are three contributions to the angular momentum of an atom.

i) Orbital angular momentum of the electrons: This corresponds to an permanent orbital angular magnetic dipole moments.

ii) Electron spin angular momentum. This corresponds to electron spin angular momentum.

iii) Nuclear spin angular momentum. This corresponds to nuclear magnetic moments.

i) Orbital angular magnetic dipole moment

Let us consider an electron describing a circular orbit of radius 'r' with a stationary nucleus at the centre as shown in fig.3.4.Let the electron rotate with a constant angular velocity of w_0 radians per second. Electron revolving in any orbit may be considered as current carrying circular will producing magnetic field perpendicular to its plane. Thus the electronic orbits are associated with a magnetic moment. The orbital magnetic moment of an electron in an atom can be expressed interms of atomic unit of magnetic moment called Bohr magneton, defined as1 Bohr magneton = $\frac{e}{2m}\frac{h}{2\pi}$ 9.27x 10^{-27}

$$= \frac{eh}{4\pi m} = \mu B$$

$$= 9.27 \times 10^{-24} \text{ Ampere } m^2$$

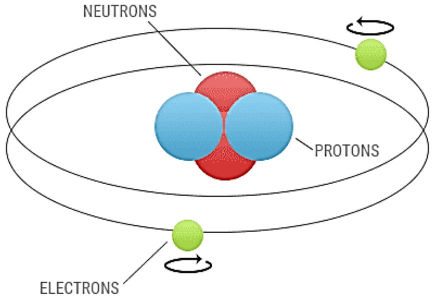


Fig The electron describing the circular orbit around the nucleus *ii) Electrons spin magnetic moment*

The concept of the electron having an angular momentum has been introduced in order to explain the details of atomic spectra. This angular momentum of the electron is referred to as the spin of the electron. Since the electron has a charge, its spin produces a magnetic dipole moment. According to quantum theory, the spin angular momentum along a given direction is either $+\frac{h}{2\pi} or -\frac{h}{2\pi}$.

Hence the spin dipole moment components along an external field are

$$+\frac{e}{m}\frac{h}{4\pi} = +1 \text{ Bohr Magneton}$$

or

$$-\frac{e}{m}\frac{h}{4\pi} = -1 \text{ Bohr Magneton.}$$

iii) Nuclear magnetic moment

The angular momentum associated with the nuclear spin is also measured in units of $\frac{h}{2\pi}$. The mass of the nucleus is larger that of an electron by a factor of the order of 10^3. Hence nuclear spin magnetic moment is of the order of 10^{-3} Bohr magnetons.For all practical purposes, we assume that the permanent magnetic dipoles arise due to the electron spin ignoring the orbital magnetic moments and the nuclear magnetic moments as their magnitude are small.

CLASSIFICATION OF MAGNETIC MATERIALS

Now we are going to study the various types of magnetic materials in terms of the magnetic properties of the atomic dipoles and the interactions between them very first distinction is based on whether the atoms carry permanent magnetic dipoles or not. Materials which lack permanent dipoles are called diamagnetic. If the atoms of the material carry permanent magnetic dipoles, such a material may be paramagnetic, ferromagnetic, antiferromagnetic or ferrimagnetic, depending on the interaction between the individual dipoles. If the permanent dipoles do not inter act among themselves, the material is paramagnetic. If the interaction among permanent dipoles is strong such that all the dipoles line up in parallel, the material is ferromagnetic. If the permanent dipoles line up in antiparallel direction, the material is antiferromagnetic or ferrimagnetic. In antiferromagnetic material the magnitudes of permanent dipoles aligned parallel and antiparallel are equal and hence the magnetization vanishes. In the case of ferrimagnetic materials magnitudes of permanent dipoles aligned antiparallel are not equal thus exhibiting magnetization.

Before studying the properties of different magnetic materials let us classify them based on their properties.

Diamagnetism

An electron moving around the nuclear results in magnetic moment. Due to different orientations of various orbits of an atom, the net magnetic moment is zero in diamagnetic materials. When an external magnetic field is applied the motion of electrons in their orbits changes resulting is induced magnetic moment in a direction opposite to the direction of applied field. Thus diamagnetism is a property of all atoms because of the influence of an applied magnetic field on the motion of electrons in their orbits. It is a weak effect and in solids it is often masked by other kinds of magnetism.

Properties of diamagnetic materials

- Permanent dipoles are absent.
- Effect is weak and often marked by other kinds of magnetism.
- When placed inside a magnetic field, magnetic lines of forces are repelled as shown in fig 2.5.
- Diamagnetic susceptibility is negative

Magnitude of susceptibility	Temperature dependence	Examples
Small negative	Independent	Organic materials, light elements
Intermediate negative	Below 20k varies with field & temp	Alkali earths, Bismuth
Large negative	Exists only below critical temperatures (Meissner effect)	Superconducting materials

- Magnetic susceptibility is independent of applied magnetic field strength.
- Relative permeability is slightly less than unity.

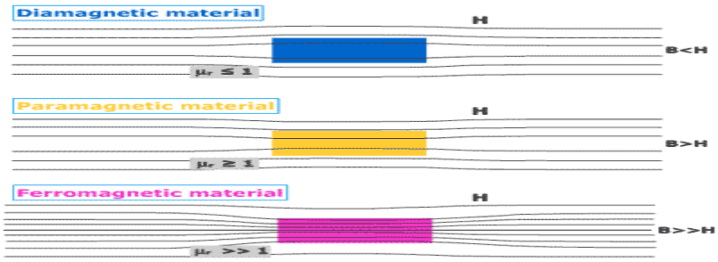


Fig. The behavior of magnetic materials in the presence of magnetic field

Paramagnetism

Each electron in an orbit has an orbital magnetic moment and a spin magnetic moment. When shells are unfilled there is not magnetic moment. In the absence of external magnetic field the net moments of the atom are arranged in random directions because of thermal fluctuations. Hence there is no magnetization. When external magnetic field is applied, there is a tendency for the dipoles to align with the field giving rise to an induced positive dipole moment. This induced dipole moment is proportional to the field. The induced magnetism is the source of paramagnetism.

Properties of Paramagnetic materials

- Paramagnetic materials posses permanent magnetic dipoles.
- In the absence of an external applied field, the dipoles are randomly oriented. Hence the not magnetization in any given direction is zero.
- When placed inside be magnetic field, it attracts the magnetic lines of force as shown in fig.

- Paramagnetic susceptibility is positive and depends greatly on temperature as detailed below.

Magnitude of Susceptibility	Temperature dependence	Examples
Small, positive, Large positive	Independent $x = \frac{c}{T}$ curie law $or\ x = \frac{c}{T-Q}$ curie-weiss law where C is curie constant and θ is curie temperature	Alkali metals and Transition metals Rare earths.

- Spin alignment is random

- Paramagnetic susceptibility is independent of the applied magnetic field strength
- Paramagnetic atoms form a collection of non-interacting magnetic dipoles.

Ferromagnetism

We have known that the permanent magnetic moment is mainly due to the spin magnetic moment. The net spin magnetic moment of ferromagnetic atoms is of the same order as magnetic moment of paramagnetic atoms. However there exists a large magnetization in ferromagnetic substance even in the absence of external applied field. This is due to spontaneous magnetization. There is a special form of interaction called exchange coupling occurring between adjacent atoms.

Properties of ferromagnetic materials

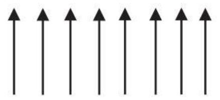
- Due to a special form of interaction called exchange coupling between adjacent atoms, even in the absence of external applied field, exhibits strong magnetization

- When placed inside a magnetic field, it attracts the magnetic lines of forces very strongly.

- Each ferromagnetic material has a characteristic temperature called the ferromagnetic curie temperature θ_f. Ferromagnetic susceptibility depends greatly on temperature above of its properties are quite different as shown below.

Magnitude of susceptibility	Temperature dependence	Examples
Very large positive	$x = \frac{c}{T-Q}$ i) For T > Q_f paramagnetic behavior ii) For T < Q_f ferromagnetic behavior	Iron, cobalt, nickel. gadolinium

- Spin alignment is parallel in the same direction



- Exhibits hysteresis
- Consists of a number of small regions which are spontaneously magnetized called domains.

Antiferromagnetism

In ferromagnetism, we have seen that the tendency for parallel alignment of the electron spins is due to quantum mechanical exchange forces. In certain materials when the distance between the interacting atoms is small, the exchange force produces a tendency for anti parallel alignment of electron spins of neighbouring atoms. This kind of interaction is encountered in antiferromagnetic and in ferromagnetic materials. The most characteristic feature of an antiferromagnetic material is the occurrence of a rather sharp maximum in the susceptibility versus temperature curve as shown in fig for MnF_2.

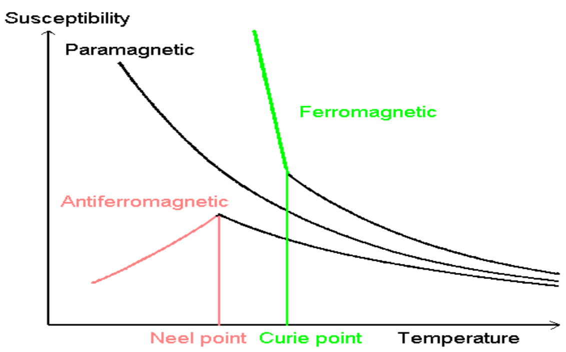


Fig. The susceptibility of MnF_2

The temperature at which the maximum occurs is called the Neel temperature,T_N. Above Neel temperature, the susceptibility is observed to follow the equation.

$$x = \frac{C}{T+\theta}$$

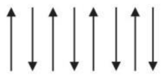
Where C is the curie constant and θ the paramagnetic Curie temperature

Properties of antiferromagnetic materials

- Electron spin of neighbouring atoms are aligned antiparallel.
- Antiferromagnatic susceptibility depends greatly on temperature

Magnitude of susceptibility	Temperature dependence	Example
Small, Positive	$x = \frac{C}{T+\theta}$ when $T > T_N$ $x \infty T$ when $T < T_N$	Salts of transition elements

- Initially susceptibility increases slightly with temperature and beyond Neel temperature the susceptibility decreases with the temperature



- Spin alignment is antiparallel.

Ferrimagnetism

This is a special case of antiferromagnetism. The net magnetization of magnetic sublattices is not zero since antiparallel moments are of different magnitudes. Hence ferromagnetic material possesses a net magnetic moment. This moment disappears above a curie temperature T_C analogous to the Neel temperature. Above T_c, analogous to the Neel temperature. Above T_C thermal energy randomizes the individual magnetic moments and the material becomes paramagnetic.

Properties of ferrimagnetic materials

- Ferrimagnetic materials possess net magnetic moment.
- Above Curie temperature it becomes paramagnetic while below it behaves as ferromagnetic materials.

Magnitude of Susceptibility	Temperature dependence	Example
Very large Positive	$y = \frac{c}{T \pm \theta}$ for $T > T_N$ Paramagnetic for $T < T_N$	Ferrites

- Ferrimagnetic domains become magnetic bubbles to act as memory elements.
- Spin alignment in antiparallel of different magnitudes.

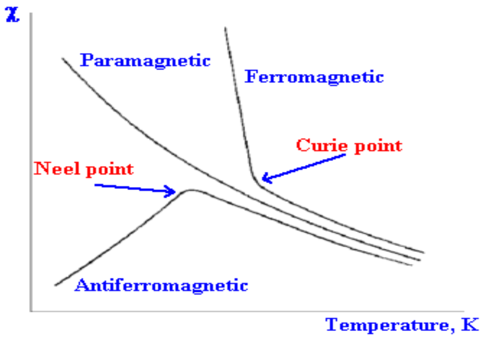


Fig. Variation of susceptibility of with temperature

DOMAIN Theory of Ferromagnetism: (WEISS Theory)

Weiss proposed the concept of domains in order to explain the properties of ferromagnetic materials and its Hysteresis Magnetic Domains.The group of atoms organised into tiny bounded regions in the ferromagnetic materials are called magnetic domains. Thus the domain is a region of the ferromagnetic material in which all the magnetic moments are aligned to produce a net magnetic moment in only one direction. Hence behaves likes a magnet with its own magnetic moment and axis. In a demagnetized ferromagnetic material, the domains are randomly orienteD and the net magnetisation, in the absence of the field, is zero. These domains are separated from other domains by a wall known as the domain wall or Bloch Wall.

When a magnetic field is applied to this material, the domains that are parallel to the applied field increase in size at the expense of the other domains and grows due to the movement of domain Walls.

Also, all the other domains aline themselves with the field. This results is large net magnetization of the material.

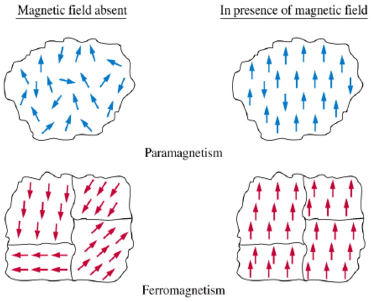


Fig. (a) Absence of field (b-c) Presence of field

Process of Domain magnetization

- By the motion of domain Walls: The volume of the domains that are favorably oriented with respect to the external field are increased than that are unfavorably oriented as shown in fig(b). Fig 2.13(a) shows domain arrangement in a virgin specimen when no magnetic field is applied.

- By rotation of domains: As shown in fig(c), when the applied external magnetic field is Strong, rotation of the direction of magnetization occurs in the direction of the field.

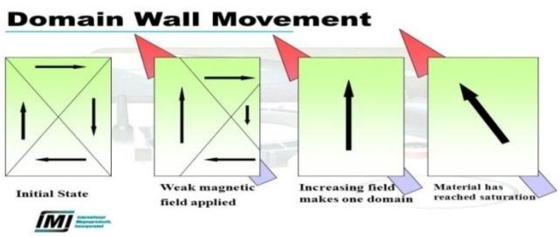


Fig (a) Random domain alignment (b) Domain wall movement (c) Domain rotation

During the growth of domain , the internal energy is due to the net contribution of magnetostatic, anisotropy, domain wall and magnetistriction energies Let us discuss the above energies and their contribution to internal energy briefly in the following section.

Types of energy involved in the process of domain growth

(i) Magnetostatic energy
(ii) Crystal anisotropy energy
(iii) Magnetostrictive energy.
(iv) Domain wall energy.

To study the domain structure clearly, we must know four types of energy involved in the process of domain growth.

(1) Magnetostatic Energy:

Magnetostatic energy or magnetic potential energy is the energy present in any ferromaganetic materials when that material produces an external field. This is due to the present of resultant dipole moment in that material even in the absence of external magnetic field.

The magnetic energy can be reduced by dividing the specimen into two domains fig(b). Further subdivisions, to N domains, reduces the magnetic energy to 1/N of the magnetic energy of the configuration.

A domain structure has 2000 magnetic energies due to the introduction of triangular domain at the top and bottom of the crystal. These triangular domain are called closure domains.

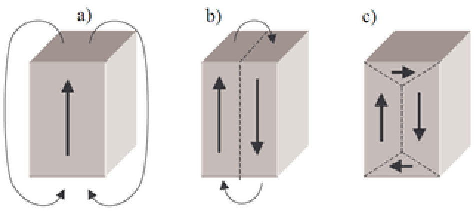


Fig Domain of magnetic materials.

(2) Anisotropy Energy:

Energy of megnetisation is the function of crystal orientation is crystals have easy and hard direction of magnetisation. For e.g. in Bcc iron, the easy direction is [100], the medium direction is [110], and the hard direction is [111].

The excess energy required to magnetise a specimen in a particular direction over that it required to magnetise it along the easy direction is called the crystalline anisotropy energy.

Material	Easy direction	Medium Direction	Hard Direction
Iron	[100]	[110]	[111]
Nickel	[111]	[110]	[100]

∴ Bloch wall or Domain wall energy = Exchange energy + crystal anisotropy energy.

(3) Magnetostrictive Energy:

The change in the dimension of a ferromagnetic material when it is magnetized is known as magnetostriction. This deformation is different along different crystal directions. So if the domains are magnetized in different directions, they will either expand or shrink. This means that work must be done against the elastic restoring force.

$$\lambda = \frac{\Delta l}{l}$$

Where λ is called the magnetostriction constant

The work done by the magnetic field against these elastic restoring force is called magneto-elastic energy (or) magnetostrictive energy. [It is the energy due to the mechanical stress generated by domain rotations].

- It is used in generation of ultrasonic waves.
- It is responsible for the noise produced by the transformer.
- It depending on the nature of the material the dimensions may either increase or decrease. For Ni rod the length decreases while for a permalloy the length increases in the presence of magnetic field. “The magnetostriction energy is the energy due to the mechanical stress generated by domain rotation.”

(4) Bloch or Domain Wall Energy:

Consider two domains in magnetic materials. These two domains are separated by Bloch or domain wall. The domains are opposite in direction. The second domain is obtained by rotating the first domain through 180°. The rotation of the domain is carried out gradually due to the existence of exchange force and anisotropy energy. The role of exchange force to rotate the dipole which is existing between the adjustment atomic spin is very ess.

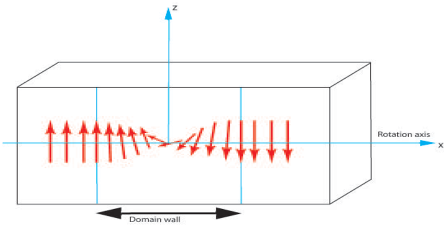
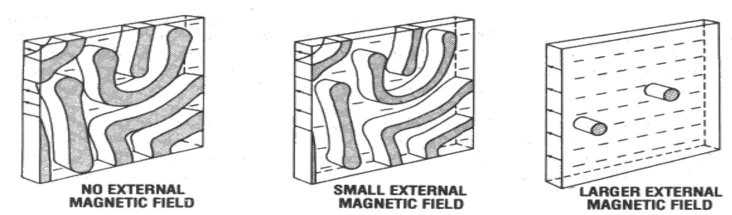


Fig Rotation of domains

The energy required to rotate domain in its easy direction. In order to rotate the domain through an angle of 180°, antisotropy energy required a thickness of domain wall nearly 1A°, where as the exchange energy requires a larger domain wall thickness. However, a minimum wall thickness is required with minimum potential energy at equilibrium thickness condition. Therefore, the minimum potential energy of domain wall is known as the domain wall energy. Generally, the thickness of domain is in the order of hundreds of A. For example, the domain wall thickness of iron is equal to 0-1 µm.

MAGNETIC BUBBLE

The garnet (semi-precious gem of deep transparent red thin film is growth on a non-magnetic substrate. It is in the form of thin films, in which the magnetic domain get concentrated into circular areas and form circular domains in the order of few microns as shown in fig 2.18. Such circular domains are called magnetic bubbles. This is used in computer memory, using soft magnetic material. They perform binary functions is Computers including logic, memory, counting and switching.



Bubble Formation: The garnet thin film is grown in the non-magnetic substrate. The magnetic domains in the garnet film arise from the preferred axis of magnetization perpendicular to the film surface.The magnetic domains are in the form of strips, which are arranged in the ways, like pointing up and down ward. When an external field is applied in a $\perp$r direction of the thin garnet film, the magnetic domains (strips) shrink down into tiny circle, known as tiny magnetic domains. The tiny magnetic domains are very small in size when compared to other magnetic storage devices like taps and hard disks. These tiny magnetic domains are known as magnetic bubbles.

The bubble memory was demonstrated in

- Orthoferrites ($RFeO_3$)

- Hexagonal ferrites ($PbFe_{12}O_{19}$)
- Gd-Co and
- Ge-Fe alloy films.

These bubbles are free to move through the film. The formation of bubbles can be observed with a polarizing microscope. The magnetic bubbles can occur only if the magnetic material has a uniaxial anisotropy with the easy axis of magnetisa perpendicular to the film surface. The diameter of this cylindrical magnetic bubble is 2μm. To store more information in the given area of the magnetic material, more number of magnetic bubbles are required in the same area. Bubble chips with more than 10 million storage cells are currently used and its read time less than 0.005 sec. The maximum velocity with which the bubble can propagate varies from V_x= 20 to 30 m/s

Bubble Propagation: Bubble operations used in chip designs are:

- Propagation
- Generation
- Transfer
- Reproduction and
- Destruction

The most basic operation is propagation. The bubble propagation circuit is known as T-bar pattern. The propagation of bubble by T-bar perm alloy pattern is shown in fig.

To control the direction of movement, magnetic 'paths' are created by deposits of magnetically. Conductive material on the surface of the thin film is in a specific pattern.

The in plane drive field producer by this permalloy T-Bar pattern is used to shift the magnetic bubbles as shown in fig.2.20. Three coils are used to rotate the in plane drive field. The bubble move to the right with the clockwise rotation of the in plane drive field and of the left with the anti-clockwise rotation of the in plane drive field. The drive field rotates in a constant velocity along the material, but the bias field and easy arts are normal to the material. The main drawbacks are

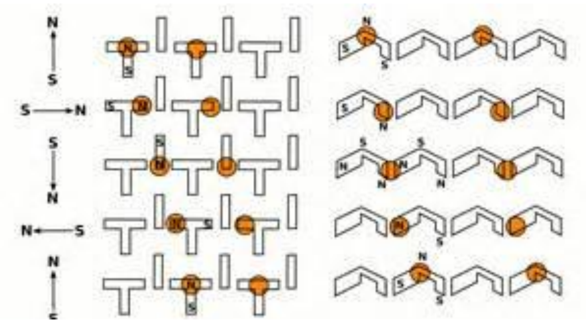


Fig. Propagation of bubble by T-bar permalloy pattern

- If required high recording and time for storing and retrieving data.
- If required interface circuits.

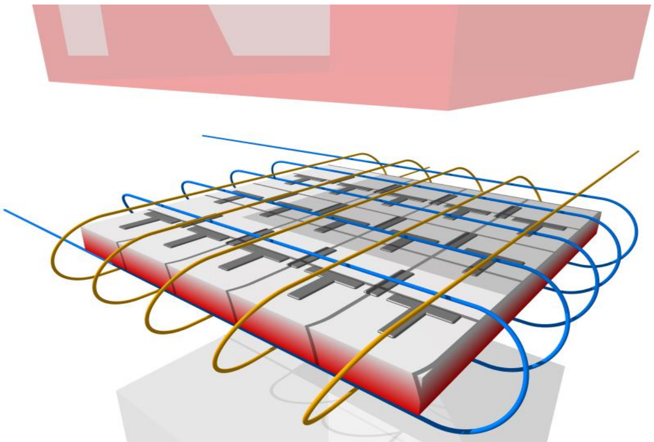


Fig. Structure of magnetic bubble memory

The data in the bubble memories are stored similar to other storage devices using the logic 0 (zero) and logic 1 (one) states. There are 3 types of fields acting on the bubble. They are.

(1) External magnetic Field or Bias Field (H_B):

A permanent magnet is used to provide the bias field which is necessary to maintain stable bubbles. It is used to reduce the volume (size) of the bubble by exerting a direct force on the bubble wall which is directed towards its centre.

(2) Effective domain (bubble) wall field (H_w):

This field is used to reduce the surface area of the bubble wall.

(3) *Magneto static (stray) field (H_A):*

It is used to equalize the overall magnetic surface change.

i.e, Surface charge on the bubble. = Surface charge in the other places of the material.

In the magnetic bubble memory, there is on major loop and 157 minor loops as shown, which are arranged from right to left. Each minor loop has 641 bubble sites. Thousands of coded characters may be stored in a single chip.

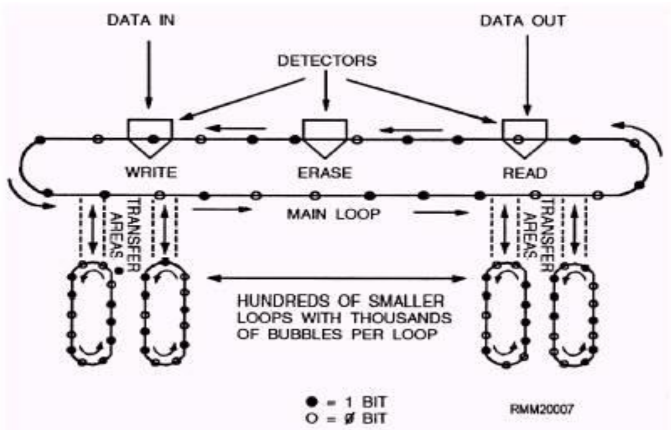


Fig. Magnetic Bubble Memory

Writing Operation

When a data has to be stored, the bubble from the minor loops are transferred to major loop and if goes to write station. In write station the message is entered and the bubble site again comes to minor loop.

Reading Operation

To read the data from the storage, the bubble from minor loops are transferred to major loop and if goes to read station, then it comes to miner loop. The data can be altered by the erase station, if we need to erase it

Special Features

- It is Non-Volatile
- Bubble sites are moved electronically
- If has high access speed.
- If can store the data even in the absence of electrical power.
- It has high storage capacity than magnetic hard disk.

MAGNETIC STORAGE DEVICES

INTRODUCTION:

Magnetic materials are widely used for storage of information magnetic taps and disks are used for the storage and reproduction of audio, video and digital sequences. It is a form of non-volatile memory. The first working magnetic recorder was invented by Valdemar Poulsen in 1898 and in 1928, Fritz Pfleumer developed the first magnetic tape recorder.

Storage devices are the computer hardware used to remember/store data.

There are many types of storage devices, each with their own benefits and drawbacks.

In general, storage device types can be separated into two broad categories:

- Permanent
- Temporary

Types of Permanent Storage Devices

Magnetic Storage Types

- Hard Disk Drive
- Magnetic Tape Device
- Floppy Disks

Flash Storage Types

- SSD (Solid State Drive)
- USB Flash Drive
- SD Card

Optical Storage Types

- Compact Disc
- DVD
- BluRay Disks

Online Storage

- Cloud Storage

Types of Temporary Storage

RAM (Random Access Memory)
ROM (Read Only Memory)

Cache memory

Nearly a dozen types of permanent storage are available for computers. On the other hand, temporary memory is often limited to Random Access Memory (RAM) and cache memory. Each type of storage or memory comes with its own benefits and disadvantages. It's important to understand what options are available on the market today and decide which solutions make sense for a given computer.

COMPUTER MEMORY CAN ALSO BE CLASSIFIED AS

Primary Vs Secondary Storage Devices

The table below summarizes the differences between Primary vs Secondary Storage Devices.

Primary Storage	Secondary Storage
Examples: RAM, ROM, Cache	Examples: Hard Disk Drive (HDD), Solid Stade Drive (SSD), CD-Rom, DVD, Blu-Ray disks etc.
Main memory in computers used to hold data that is currently in use.	Long term storage to hold data and programs that might not be used currently but they can be used in the future.
Provides the fastest data access in computers.	Not as fast as Primary Storage.
Located on the motherboard or on the CPU.	Located on separate hardware storage devices.
Data is usually lost (except ROM) when power is off.	Data is not lost when power is off.
Limited storage size.	Larger storage size.
Example Primary Storage Size (e.g RAM): 4GB to 128GB	Example Secondary Storage Size: 512GB to 1TB

The storage media is typically called a disk or a cartridge. The process of storing and retrieving data in a memory unit is called writing and Reading (R/W) magnetic storage uses a drive in which there is motor to rotate the media at a high speed. It accesses the stored information using a small devices called heads.

Read / write Head (R/W):

Each head has a tiny electromagnet, which consists of an iron core wrapped with wire as shown an fig. The electromagnet applies a magnetic flux to the oxide on the media and the oxide permanently "remembers" the flux it sees. During writing, the data signal is sent through the coil of wire to create a magnetic field in the core. At the gap, the magnetic flux forms a fringe pattern. This pattern bridges the gap, and the flux magnetizes the oxide on the media when the data is read by the drive, the read head pulls a varying magnetic, field across the gap, creating a varying magnetic field in the core and therefore a signal in the coil. This signal is then sent to the computer as binary data.

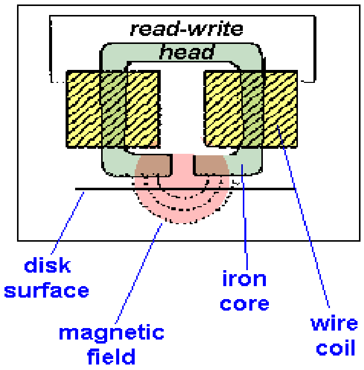


Fig. Read/Write Head

Important magnetic parameters for recording:

The important parameters for recording are

- Soft magnets should be used for temporary storage and hard magnets should be used for permanent storage.
- Electromagnetic induction should take Place in that materials.
- The material must be easily magnetisable in nature.
- It should posses magneto-resistance ie, its electrical resistance should vary with respect to magnetization.

Magnetic Disk Devices

Magnetic disk devices are direct access storage devices: They are magnetically coated. There are two types of disks

1. Compact Disk
2. Hard disk
3. Floppy disk

1.Compact Disk

CD, DVD and Blu-Ray drives are optical storage devices.

Binary data is stored as changes to the texture of the disc's surface, sometimes thought of as microscopic pits and bumps.

Disc capacities

In the pursuit of larger optical storage capacities, DVDs were created, followed by Blu-Ray.

CD	DVD	Blu-Ray
700 MB	4.7 GB	25 GB – 128 GB

Compact Disks (CDs) are known as optical storage devices. The disks feature microscopic pits and bumps that disk drives read as binary data. While running in an optical disk drive, CDs rotate at a constant speed. A laser glides over the surface of the disk to read the binary data. An optical lens reads this data and sends it to the computer or laptop being used. Depending on the disk type, CDs can be read only or read/write capable. CDs typically contain audio and other small amounts of data. Storage capacity is limited to 700 MB, so they're not suitable for high definition video storage. Luckily, CDs cost very little money and take up very little space. They're prone to scratches that render the disk unreadable, which leads to reliability problems. Not all computers and laptops feature an optical disk drive today, either. Better disk-based storage options are available. Typical Storage Capacity: 700 MB

2. Hard Disk: A hard disk is also a permanent Storage, where we can store lot of information. Storage capacity of a hard disk is measured in mega bytes(MB) or Giga bytes(GB). They are available in different sizes.

Structure: A magnetic hard disk is made up of a very thin disk using metals and metal alloys. Soft magnetic materials are coated on both sides of the disk. The disk consists of thousands of concentric circles with increasing diameter from the centre. These are known as reading tracks. The data stored in the reading tracks using the read / write arm as shown in fig. Similar to the floppy disk, the hard disk is also divided into sectors.

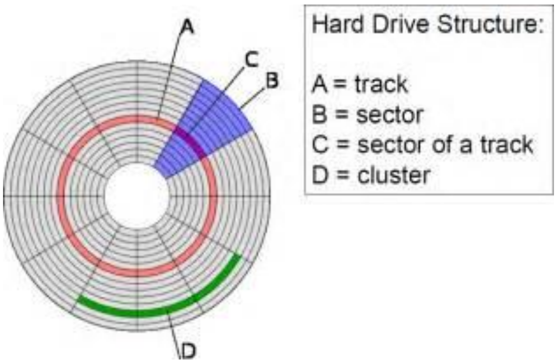


Fig. Magnetic hard disk

Generally, the storage Capacity of the single disk is very low. But it is increased by making a number of the data is written (or) read by the R/W heads in the horizontal sensing arms by moving in and out between the platters. The precaution is that the R/W head doesn't touches the surface instead, it fly over the disk surface by a fraction of a mm. The hard disk once installed in the system, cannot be removed easily.

Advantages:

- ❖ Data can be read directly from any part of the hard disk (Random access)
- ❖ They are safe and prevented from dust, since they are seated in special Chamber.
- ❖ Very high speed in reading and writing the information.

- ❖ It has very large storage capacity.
- ❖ Thousands of files can be permanently stored.
- ❖ The access speed is about 1000 KB per second.

Disadvantages:
- ❖ If the data is corrupted then it is difficult to retrieve.
- ❖ It is very costly.

Disks on a single driver unit as shown in fig. This driver unit is called the disk pack. The disk pack is enclosed in a dust free air tight container.

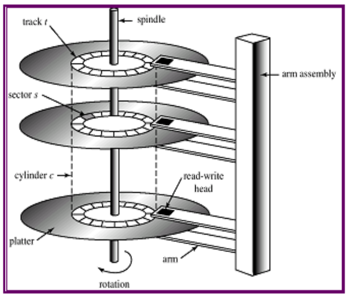


Fig. Moving hard disk mechanism

Working: The magnetic hard disk pack consists of a number of disks, read write head and moving arm. The disks are rotated using the disk drive unit. Each disk is having a read/write head which is attached with a moving arm as shown in fig. The moving arm helps to select the particular disk and sector for recording and reading purpose. The amount of data stored in a hard disk depends on its capacity. The different types of hard disk and its storage capacity are given below.

Hard disk size and storage capacity

S. No	Size in inches	Storage Capacity
1.	1.8	160 GB
2.	2.5	500 GB
3.	3.5	500 to 1000 GB

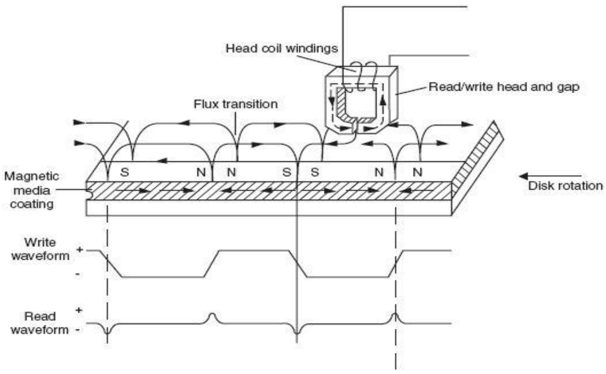


Fig. Flying head of a magnetic hard disk

Floppy Disk (or) Diskette

Floppy disk are the type of secondary storage devices. It is made up of a Flexible Plastic material and hence called as Floppy Disk. It acts both as an input and output device.

Structure of Floppy Disk

A floppy disk is made of flexible plastic which is coated with magnetic oxide. It is provided with a central hole. This hole is used for mounting the disk in the floppy drive unit. It is enclosed in a flexible square envelop (cover). This cover prevents the disk from dust and moisture. There is a small index hole in the cover and there will be a hole in the drive disk. When these two holes matches then only the storage operation starts. There is a opening called Read/Write head aperture slot. The reading and writing operation is done in floppy disk through this opening. The write protect notch is used to prevent writing on the disk by other users, which can be done by covering the notch with a sticke

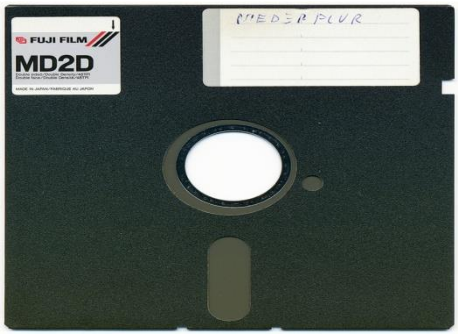


Fig Full view of Floppy

Operation

When the floppy is put into the drive, and when the drive is operated, the disk inside the cover is rotated. There are 200 to 800 tracks on the disk surface, each of which has a designed location number, as shown in fig.2.28. The Read/Write operation is done by the Read/Write head in the drive unit. The head is a small electromagnet with minute gap between the poles.

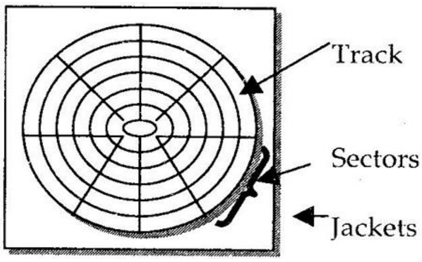


Fig. Floppy tracks

Writing operation: The floppy disk moves over the gaps as shown in fig.2.29. When it moves, electric pulses from the CPU flow through the write coil of the head and magnetises the iron oxide coating in the disk to the proper pattern.

Reading Operation: When the datas are to be read, the magnetised patterns induces pulses of current in the read coil and is amplified then to the CPU. Read/Write of a frequency modulated wave is as shown in fig.

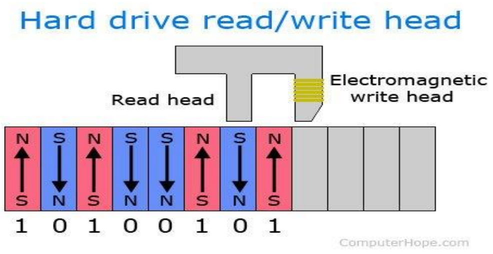


Fig. Floppy read/write head.

Thus Data can be stored and accessed from the floppy disk on both sides (and) single side.

Types of floppy disk:

Depending upon their storage capacities type are classified as follows.

S. No.	*Storage Capacity*	*Size*	*Technical term*
1.	*3.5*	*720 KB*	*Double Sided double density*
2.	*3.5*	*1.44 MB*	*Double Sided High density*
3.	*5.25*	*160 KB*	*Single Sided Single density*
4.	*5.25*	*360 KB*	*Double Sided Double density*
5.	*5.25*	*1.2 MB*	*Double Sided High density*

Special Advantages:

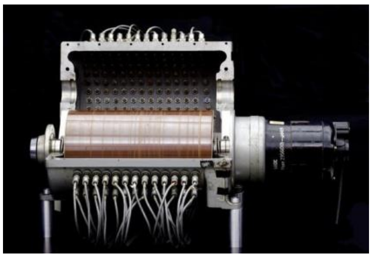
- ❖ *Non-volatile storage medium.*
- ❖ *The cost is very low.*
- ❖ *It can be easily handled.*

Disadvantages:

- ❖ *Here the magnetic disk is rotated mechanically.*
- ❖ *It has low storage capacity.*
- ❖ *Now a days the usage is reduced because of other secondary devices.*
- ❖ *It has insecquired data storage.*

Magnetic drum

The magnetic drum memory was invented by the Austrian engineer Gustav Tauschek (1899-1945) in 1932 in Austria. Tauschek was a genius self-taught Viennese engineer, who besides the drum-memory, invented also many devices and systems for the punch-card machinery, as well as the first OCR (Optical Character Recognition) the machine in 1928, the so-called Reading Machine.



A Magnetic Drum Memory refers to the magnetic data storage device used by early computers. It functioned as the main working memory, similar to the modern RAM cards (random access memory). In other instances, the magnetic drum memory served as secondary storage.

But later on, the magnetic core memory and hard disk drives came into existence and replaced the drums. That's because they offered better size balance, reliability, high speed, and had the potential for further enhancements. Besides, they had a denser storage capacity than drums. And due to that, the manufacturing of drums stopped in the 1970s.

Magnetic Drum Memory: How It Worked

The device consists of a metal drum coated with a ferromagnetic recording material. Its controller selects the proper head and waits for the data to appear beneath it as the drum turns. On the other hand, stationary write heads release electrical pulse, changing the magnetic orientation of a particle at a given position on the drum. Finally, the read heads recognize a particle's orientation as, either binary 1 or 0.

- Magnetic drum memory had a capacity of about 62.5 KB.
- The data storage device could store 500000 bits across its total surface
- The principles at work in magnetic drum memory helped to lead researchers to create another and even more important innovation: the hard disk drive.

The SuperDisk

The SuperDisk, also marketed as LS-120, was a high-speed, high-capacity alternative to the 3.5 inch, 1.44 MB floppy disk. Introduced in the mid-1990s by Imation, 3M's storage products group, it was not as successful in North America as it was in Asia and Australia. Several original electronic manufacturers (OEMs) supported it--Compaq, Dell, and Gateway were a few that did. Even though the SuperDisk drive was backwards compatible with 1.44 MB and 720KB floppy formats, the popularity of Iomega's Zip drive kept it from dominating the floppy storage market.

By the 2000s the price of CD-R, CD-RW, and solid-state USB flash drives dropped to a point that made magnetic disks no longer competitive.

MRAM, Magneto-Resistive Random Access Memory

MRAM (magnetoresistive random access memory) is a method of storing data bits using magnetic states instead of the electrical charges used by devices such as dynamic random access memory (DRAM). By combining the high speed of static random access memory (SRAM) and the high density of DRAM, MRAM promises to significantly improve electronic products by storing greater amounts of data, enabling faster data access and consuming less energy than existing electronic memory.

MRAM is any RAM system which takes advantage of an electron screening effect that occurs when a current is passed through a pair magnetic domains. A magnetic domain acts as a single bar-magnet, domains are said to point in a direction based on the orientation of this internal 'magnet'. Magnetism is generated by a property of electrons called spin. If a current is passed through a magnetic domain, only electrons that are spin-oriented (pointing) in the same direction as the domain are able to easily pass through to the other side.

MRAM concepts pass current through two magnetic domains
If the two domains are pointing the same direction, then any electron that makes it through the first domain will be able to pass un-hindered through the second domain. This is a low-resistance path for the current to go through. If the two domains are pointing in different directions, then only electrons which are 'flipped' or have some intermediate value (or are lucky, whatever that means for electrons) can be transmitted through both domains. This is a high-resistance path for the current to go through.

If you call High-resistance paths 1 and Low-resistance paths 0, and you are able to independently change a High-resistance path to a Low-resistance path by flipping a domain to point in a different direction, you can build a memory element.

MRAM, Magneto-Resistive Random Access Memory, is a type of non-volatile memory (NVM) capable of holding saved data even if the power is down or the power is accidentally cut off. MRAM — also called Magnetic RAM — is not new. It has been in the market for more than two decades, but there have been several recent developments in the technology allows MRAM to be used successfully in specific emerging applications, as well as in not-so-new ones.

Current STT-MRAM devices already have the advantage of being faster and lower power than NVM flash memory devices. They also have the potential to compete against volatile memory devices such as SRAM and DRAM, not only because they could be faster but because they can be scaled-down even below 10 nm. This feature makes them even more attractive to embedded memory applications.

SUPERCONDUCTING MATERIALS

Introduction

The initial discovery of superconductive materials was made in the year 1911. Before 1986, the critical temperatures for all known superconductors did not exceed 23 Kelvin. Before the discovery and development of high temperature superconducting (HTSC) materials, the use of superconductivity had not been practical for widespread commercial applications, except for Magnetic Resonance Imaging (MRI) and Superconducting Magnetic Energy Storage (SMES) applications, principally because commercially available superconductors (i.e. low temperature superconducting (LTSC) materials) are made superconductive only when these materials are cooled to near 0K. Although it is technologically possible to cool LTSC materials to a temperature at which they become superconductive, broad commercialization of LTSC materials has been inhibited by the high cost associated with the cooling process. For example, liquid helium, which can be used to cool materials to about 4K, and which has been commonly used to cool LTSC materials, is expensive and relatively costly to maintain.

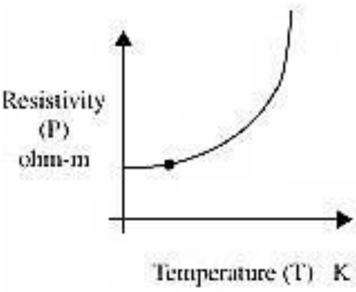
In 1986, a breakthrough in superconductivity occurred when two scientists, Dr. K. Alex Muller and Dr. J. Georg Bednorz, identified a ceramic oxide compound which was shown to be superconductive at 36K. This discovery earned them a Nobel Prize for Physics in 1987, which is one of four Nobel Prizes that have been awarded for work on superconductivity. A series of related ceramic oxide compounds which have higher critical temperatures were subsequently discovered.

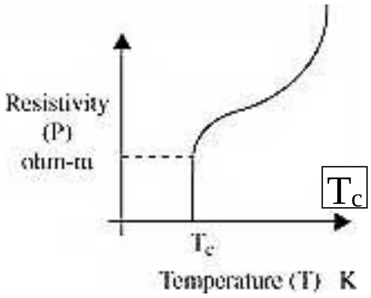
SUPERCONDUCTING MATERIALS AND TRANSITION TEMPERATURE (T_c)

The electrical resistivity of pure metals decreases gradually with decrease in temperature and reaches a low but measurable resistivity values at temperatures nearing zero Kelvin. However there are few materials for which the electrical resistivity at a very low temperature abruptly plunges from a finite value to zero and remains there upon further cooling. This phenomenon is called Superconductivity. Materials that display this behaviour are called superconducting materials. The temperature at which there is abrupt drop in resistivity to zero value is called as superconducting transition temperature (T_c). At T_c, the materials get transformed from one conducting state to another. Thus zero resistivity or infinite conductivity is observed in a superconductor at all temperatures below a critical temperature (**ρ**= 0 for all $T < T_c$).

At Transition temperature T_c,

1. The electrical resistivity of the material abruptly drops to zero.
2. The magnetic flux lines are excluded from the material.
3. There is a discontinuous change in specific heat capacity.
4. There are small change in thermal conductivity and volume of the material.





OCCURRENCE OF SUPERCONDUCTIVITY

The occurrence of superconductivity was first discovered by Heike KamerlingOnnes in 1911. He liquefied Helium gas in 1908 whose boiling point is 4.2 K. He studied the properties of metals under low temperatures using liquid helium. In 1911, when he studied the electrical properties of solid mercury at very low temperatures, he found that the resistivity of mercury suddenly decreases 10^5 times around 4.2 K.

This drastic change in electrical resistivity of mercury indicates that mercury gets transformed from conducting state to superconducting state with the transition temperature of 4.2 K.

Since then, research is being aimed at getting the T_c nearer to room temperature. If the material is having low T_c (< 30 K) value, then the material is called low T_c superconductor. If the material is having high T_c (> 30 K) value, then the material is called high $T_c$superconductor.

The evolution of superconducting transition temperature (T_c) since its discovery.

Material	Transition temperature (T_c) in K	Year
Elements	Type I Superconductors	
Hg	4.2	1911
Pb	7.196	1913
Nb	9.46	1930
Compounds	Type II Superconductors	
NbN	16.0	1941
V_3Si	17.4	1950
Nb_3Sn	18.3	1956
Nb_3Ge	23.0	1935
Ceramics	Type II Superconductors	
La-Ba-CuOPerovskites	35.0	1986
Y-Ba-CuOPerovskites	92.0	1987
$Bi_2Sr_2Ca_2Cu_3O_{10}$	107	1988
$Bi_2Sr_2CaCu_2O_9$	110	1988
$Tl_2Ba_2Ca_2Cu_3O_{10}$	127	1988
$Hg_{12}Tl_3Ba_{30}Ca_{30}Cu_{45}O_{127}$	138	2006
$HgBa_2Ca_2Cu_2O_8$	153	2006
$(Tl_4Ba)Ba_4Ca_2Cu_{10}O_y$	240	2009

Note that the transition temperature of Y-Ba-CuOperovskites is 92K which is 15K above the boiling point of liquid nitrogen (77 K). The liquid nitrogen environment is far easier to handle and cheaper than liquid helium. Further it consumes about 25 times more energy to cool from 77 K to 4 K than from room temperature to 77 K.

PROPERTIES OF SUPERCONDUCTING MATERIALS

1 Zero Electrical Resistance

The DC electrical resistance of a superconductor at all temperatures below a critical temperature is practically zero. The transition from normal state to superconducting state occurs sharply in pure metals whereas it is not so in impure, HTSC oxides. In HTSC oxides, there exist several superconducting phases.

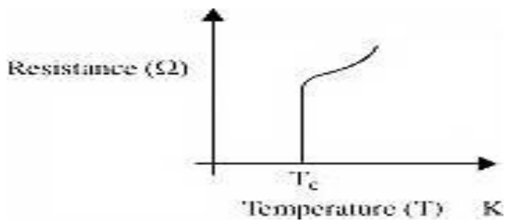


Fig Variation of resistance with temperature

Consider a small amount of current applied to a superconducting ring. Since the ring is in superconducting state, it has zero resistance. Hence the superconducting current through the ring will keep on flowing without any appreciable change in its value. Such a current is said to be persistent current. e.g. Dr.Collins experimentally found that the resistance of a superconducting ring by passing standard current through it. $[(R_{scs} / R_{ns}) < 10^{-5}]$ where R_{scs} is the resistance of the material in superconducting state and R_{ns} is the resistance of the material in normal state. He observed that, the value of the current in the superconducting ring does not change for more than 2.5 years. This shows that, the superconductor has virtually zero electrical resistance and they can conduct electricity without resistance.

2 Diamagnetic Property (Meissner Effect):

When a weak magnetic field is applied to a superconducting material at a temperature below transition temperature ($T < T_c$), the magnetic flux lines are excluded from the material ($B = 0$). So the superconductor acts as an ideal diamagnet. The ejection of magnetic lines of force, when the superconducting material is cooled below its T_c in a weak magnetic field is called Meissner effect.

Generally, magnetic flux density inside the material = $B = \mu_0 (H+I)$

Here, magnetic flux density inside the superconductor = $B = 0$

$\mu_0 (H+I) = 0$

μ_0 is the permeability of free space = constant, So $\mu_0 \neq 0$

Then $(H+I) = 0$ and $H = - I$

Magnetic susceptibility of the superconductor = $\chi_m = (I/H) = I/(-I) = (-1)$

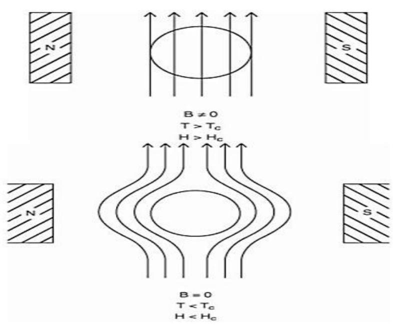


Fig. (a) Magnetic field applied to a normal conductor (b) Magnetic field applied to a superconductor

For a diamagnetic material, χ_m is negative. So at $T < T_c$ and $H < H_c$, the superconducting material behaves like a perfect diamagnetic material.

3 Effect of Heavy Magnetic Field:

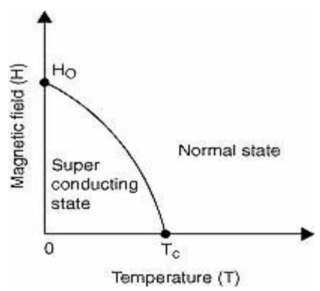


Fig. Dependence of critical magnetic field with temperature

Below T_c, superconductivity can be destroyed by the application of strong magnetic field. At any temperature, the minimum magnetic field required to destroy superconductivity is called critical field (H_c) of the material. Thus the value of $H_c$depends upon the temperature of the superconducting material and is given by $H_c = H_0 [1 - (T^2 / Tc^2)]$ where, H_0 is the critical field at 0 K, T is the temperature of the material and T_c is the transition temperature. From the graph, we know that, when the temperature of the material increases from 0 K, the value of Hc decreases and at $T = T_c$, $H_c = 0$. Also the value of H_c is different for different materials.

4.Effect of Heavy Current (Silsbee's rule):

We know that a current carrying conductor has a magnetic field around it. When heavy current flows through a superconductor it will set up the magnetic field which destroys the superconducting property of the superconductor. According to Silsbee's rule, the critical current (I_c) flowing through a superconducting wire of radius r is $I_c = 2\pi r H_c$ where, H_c is the critical field at T K.

5 Effect of Pressure:

Some materials which behave as normal conductors at normal pressure can undergo phase transition and behave as superconductors under the application of external pressure. *e.g.*

- Cesium becomes a superconductor at 110 kilo bar pressure and its $T_c = 1.5$ K
- Silicon becomes a superconductor at 165 kilo bar pressure and its $T_c = 8.3$ K

5.Effect of Isotope:

The transition temperature of the given superconducting material varies with its mass number or isotopic mass and this effect is known as Isotope effect. Maxwell found that, T_c is inversely proportional to the square root of the atomic mass (M) of the isotope of the single superconductor. *i.e.*$T_c \propto [1 / M^{½}]$

For *e.g.* Mass number of mercury varies from 199.5 to 203.4 amu and the corresponding transition temperature $T_c$varies from 4.185 to 4.146 K respectively. Obviously the existence of isotope effect indicates that although the superconductivity is an electronic phenomenon, it depends on the vibration of the crystal lattice (phonons) in which the electrons move.

6 Entropy:

Entropy is a measure of degree of disorderness of the given system. The entropy of a superconducting material is found to be lower than that of the normal conducting material which indicates that in the superconducting state the electrons are in the more ordered state than they are in the normal conducting state.

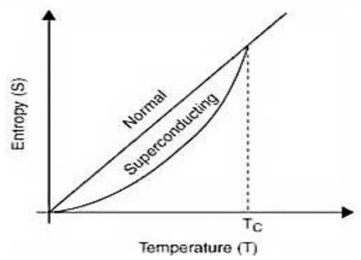


Fig. : Variation of entropy with temperature

7 Specific heat capacity:

The specific heat capacity of a normal conductor (C_n) consists of two contributions, one from the conduction band electrons and the other from the lattice.
i.e. $C_n = C_n^{(electrons)} + C_n^{(lattice)}$; 'n' represents normal conductor.

i.e. $C_n = \sqrt{T} + \exp T^3$ where $\sqrt{T}$ arises from electron contribution and $\exp T^3$ arises from lattice contribution.

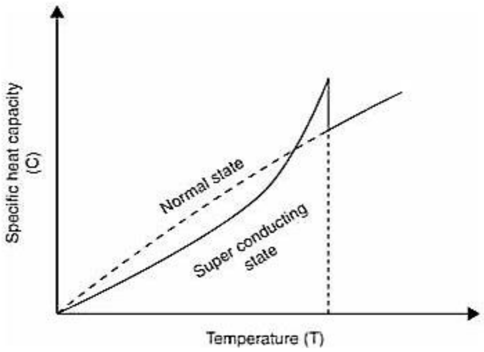


Fig. : Variation of Specific heat capacity with temperature

Consider the specific heat capacity of a superconductor (C_{es}) which varies in a characteristic way at T_c. It is given by $C_{es}(T < T_c) = A\ e^{-(\Delta / K_B T)}$ where K_B -Boltzmann constant, T- temperature of the specimen, Δ- a gap in the spectrum of allowed energy states separating the excited states from the ground states. From above equation, there appears a discontinuity in specific heat at T_c.

8 Energy gap:

Specific heat capacity measurements provided the first indication of an energy gap (Δ) in superconductors. The energy gap of a superconductor is of different nature than that of a semiconductor or a conductor. In case of semiconductors, the energy gap is tied to the lattice and it corresponds to the energy difference between the valence band and the conduction band (~1eV); whereas in superconductors, the energy gap (Δ) is tied to the Fermi energy and this gap in the spectrum of allowed energy states separates the excited states from the ground states. In conventional superconductors, Δ~1meV while in HTSC, Δ~1to 10 meV.

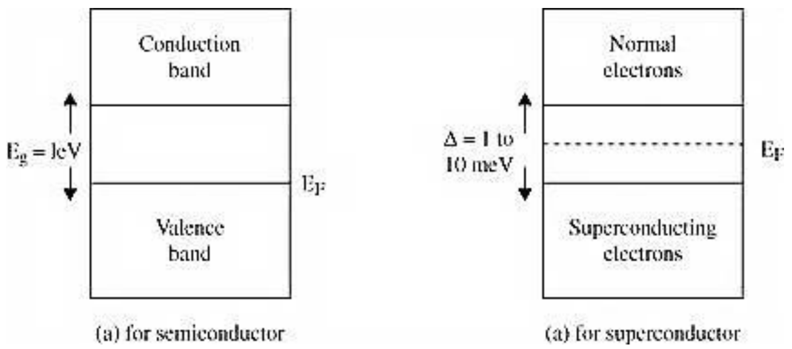


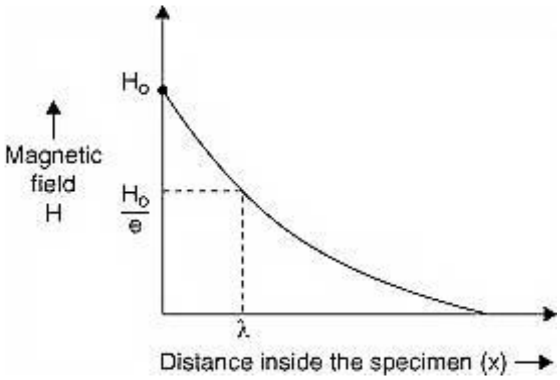
Fig. Band Gap

9 London Penetration Depth (λ)

When a superconducting material is placed in a magnetic field, a current is set up on the surface of the material and a magnetic field is produced everywhere within the material. This magnetic field opposes the applied external magnetic field. So the applied magnetic field penetrates some distance into the superconductor. This distance is called London Penetration depth (λ). It is also defined as the effective depth to which a magnetic field penetrates a superconductor.

$H_{(x)} = H_o\, e^{-(x/\lambda)}$ where $H_{(x)}$ and H_o are the magnetic fields at a distance 'x' and on the surface. $\lambda = 10^3$ to 10^4 Å; λ is independent of the frequency of the magnetic field but dependent on temperature.

$(\lambda_T / \lambda_o)^2 = 1 / [1 - (T/T_c)^4]$ where λ_T and λ_o are the penetration depth at T K and 0 K.



Coherence Length (ξ):

The paired electrons (Cooper pairs) are not scattered because of their peculiar properties of smoothly riding imperfection. Also there is no exchange of energy between them. Mean time, they can maintain their coupled motion up to certain distance (about 10^{-6} m). This distance is called Coherence Length. It is also refereed as the distance between two electrons of the Cooper pair within the highly coherent superconducting state and is given by $\xi = (\hbar V_F) / (\pi \mathbf{\Delta})$ where $\hbar = h/2\pi$, V_F is the Fermi velocity and $\mathbf{\Delta}$ is the superconducting energy gap.

11 Ginzburg Landau Parameter (k):

It is the ratio of London penetration depth (λ) to coherence length (ξ). $k = \lambda/\xi$. If $k < (1/\sqrt{2})$, the material is type I superconductors, and if $k > (1/\sqrt{2})$, the material is type II superconductors.

Flux Quantization:

The magnetic flux ϕ through a superconducting ring is quantized in terms of h/2e. This phenomenon is said to be flux quantization. A closed superconducting ring (loop) can enclose magnetic flux only in integral multiples of a fundamental quantum of flux. This fundamental quantum of flux is called Fluxon (ϕ_o).

$$\phi_o = (h/2e) = [6.626 * 10^{-34} /(2 \times 1.602*10^{-19})] = 2.068*10^{-15} \text{ Weber.}$$

The magnetic flux enclosed by a superconducting ring is $\phi = n\, \phi_o = n\, (h/2e)$. The quantization of magnetic flux has been confirmed experimentally. The magnetic flux produced in an ordinary solenoid or transformer is not quantized.

Thermal Conductivity:

The thermal conductivity undergoes continuous changes between the normal state and superconducting state of the given superconducting material. It usually lowers in the superconducting phase and approaches zero at very low temperatures of the specimen. This suggests that, superconducting electrons (Cooper pair) possibly play no role in heat transfer.

Other properties:

- Skin Effect: In the superconducting state, superconductor expels the magnetic flux. Hence, DC current flows only over the outer surface of the superconductor. This effect is called Skin effect.

THEORY OF SUPERCONDUCTIVITY

A number of theories have been put forward to describe the phenomenon of superconductivity *viz*. London theory, Ginzburg and Landau theory and BCS theory. BCS theory explains most of the phenomena associated with superconductivity in natural manner but alone could not explain the anomalous behavior of HTSC. To explain the HTSC, several theories have been proposed like Resonance Valence Bond (RVB) theory, Interlayer tunneling model, Boson Fermion model *etc*. None of these models provide satisfactory explanation of the anomalous features of HTSC oxides. However, the efforts to understand the HTSC oxides pairing mechanism with enhancing future prospects for new HTSC materials and their novel applications are still under research and are in progress.

The theory of super conductivity can be considered in two stages like macroscopic and microscopic. The first stage is to accept the macroscopic description of a superconductor as a body which has no magnetic and electric fields (B = 0 = E) and to develop the thermodynamic consequences without making any assumptions. The second stage is the microscopic description of a superconductor formulated by Bardeen, Cooper and Schrieffer (BCS) on the basis of advanced quantum theory.

1 London's Theory (Macroscopic)

London formulated a more general description of electro-dynamic behavior of superconductor. At an extremely low temperature, vibrations of the nucleus and free electrons of certain atoms slow down so much and they synchronize with the passing waves of electrons in the flow of electric current. When this happens resistance to electric current disappears.

The BCS Theory (Microscopic)

BCS theory is a quantum mechanical theory and it was proposed by Bardeen, Cooper and Schrieffer in the year 1957. It comes from the experimental results of superconducting behavior of materials namely (a) Isotope effect and (b) variation of specific heat with temperature.

When we consider the isotope effect, we find that two different isotopes of the same materials exhibit different transition temperatures. Why is the mass of the atom involved in pure electronic phenomenon- superconductivity? Obviously, it means that the motion of the positive ions (phonons) in the lattice has to do something with superconductivity.

Heat capacity measurements provided the first indication of energy gap in superconductors. *i.e.* exponential temperature dependence of specific heat is a hall mark of the system with as an energy gap in the spectrum of allowed energy states separating excited states from the ground states.

BCS theory is based on the interaction of two electrons through the intermediary of phonons. When an electron approaches an ion in the lattice, there is a coulomb attraction between the electron and the lattice ion. This produces a distortion in the lattice and causes an increase in the density of ions in the region of distortion. The higher density of ions in the distorted region attracts, in its turn, another electron. Thus a free electron exerts a small attractive force on another electron through a phonon is called Cooper pair. These pair can drift through the crystal without any scattering over the lattice imperfections without exchanging energy with them, *i.e.* their movement is without resistance.

At normal temperatures, the attractive force is too small and pairing of electron does not take place. Each cooper pair consists of two electrons of opposite spins and momenta. At very low temperatures, such pairing is energetically advantageous. In a typical superconductor, the volume of the given pair encompasses as many as 10^6 other pairs. These dense clouds of Cooper pairs form a collective state where strong correlations arise among the motions of all pairs because of which they drift cooperatively through the material.

Thus superconducting state is an ordered state of the conduction electrons. The motion of all Cooper pairs is the same. Either they are at rest, or if the superconductor carries a current, they drift with identical velocity. Since the density of Cooper pairs is quite high, even large currents require only small velocity. The small velocity of Cooper pairs combined with their precise ordering minimizes collision processes. The extremely rare collision of Cooper pairs with the lattice leads to vanishing resistivity.

Electron-Lattice- Electron (Electron-Phonon- Electron) Interaction:

Bardeen found that, an electron moving through a crystal lattice has a self energy accompanied with "Virtual Phonon" of energy hυ. Let us consider an electron of wave vector K_1 moving through a crystal lattice. This electron can distort the lattice and a virtual phonon of wave vector q is emitted. Thus K_1 is scattered as $(K_1 – q)$. Consider a second electron of wave vector K_2 is moving through a crystal lattice and close to the previous electron wave vector K_1. Now the virtual phonon q is absorbed by this second electron and K_2 is scattered as $(K_2 + q)$. Thus the second electron interacts with the first electron *via* lattice deformation and the exchange of virtual phonon between the two electrons. This type of interaction is called Electron-Lattice- Electron (Electron-Phonon-Electron) Interaction.

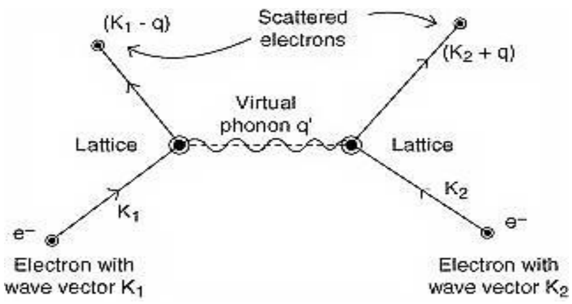


Fig. Electron-Phonon- Electron Interaction

Total wave vector before interaction = Total wave vector after interaction

$$K_1 + K_2 = (K_1 - q) + (K_2 + q) = K_1 + K_2$$

Thus net wave vector of the two electrons (pair of electrons) is conserved and the momentum is transferred between these two electrons. So these two electrons together form a pair called Cooper pair.

The energy of the Cooper pair (E_{cp}) is less than the total energy of separated electrons (E_{sep}) in the normal state. ($E_{cp}<E_{sep}$). So the binding energy of the Cooper pair (E) is the energy difference between the normal state and paired state ($E=E_{sep}–E_{cp}$). Also this energy is required to break the

Cooper pair. At T >T_c, all the free electrons are in the separated position. At T <T_c, electron-lattice-electron interaction is stronger than electron-electron repulsive coulomb interaction. So the free electrons tend to pair up (formation of Cooper pair). Then the pairing is complete at T = 0 K.

Existence of Energy Gap:

Fermi Energy (E_F) is the highest energy to which the electrons are filled in a metal. The corresponding energy level is called Fermi Energy level. The loci of the end points of the wave vectors corresponding to the Fermi level trace out a surface called Fermi Surface. The binding energy of the Cooper pair ($E = E_{sep} - E_{cp}$) appears as the superconducting energy gap at the Fermi surface. At the Fermi surface, the normal electron states are above the energy gap while superconducting states are below the energy gap. According to BCS theory, this energy gap at absolute zero is predicted to be $\Delta = 3.5\ K_BT_c$ where K_B is the Boltzmann constant.

The width of the energy gap (Δ) is a function of temperature. At T >T_c, Cooper pairing is dissolved and hence the energy gap reduces to zero (Δ = 0). At T = 0 K, all the free electrons are formed in a Cooper pair and hence the energy gap reaches the maximum (Δ = maximum)s. The energy gaps for typical superconductors (~10^{-4}eV) are much smaller than the energy gaps for typical semiconductors (~1eV). This prediction of the superconducting energy gap was verified experimentally by studying absorption of electromagnetic radiation by superconductors.

Major accomplishments of BCS theory

- BCS theory explained Meissner effect, coherence length, penetration depth, flux quantization and energy gap parameter.
- It has solved the problem of electron energy where there is attractive interaction.
- It gives the expression for the transition temperature (McMillan's formula),

$T_c = 1.14\ \theta_D \exp\ [-1/V.N(E_F)]$ where θ_D - Debye temperature, V- net attractive potential of the electron, $N(E_F)$ – density of states at the Fermi level.

GENERAL APPLICATIONS OF SUPERCONDUCTORS

1.Engineering:

(a). When superconductors are used as electric cables, the losses (due to I^2R) are avoided and electrical power transmission can be done at a lower voltage level or a long distance.
(b). Superconductors are used in relay switching circuits since superconducting property can be easily destroyed.
(c). Superconductors are used in gating circuits, storage device in computers etc.
(d). Superconducting coils in transformers and electrical machines much stronger magnetic fields than coils made by other materials since losses due to eddy current and hysteresis are very low. So the size and weight of the motors and generators will be reduced and they will be more efficient.
Medical:

(a). Superconductors are used in NMR (Nuclear Magnetic Resonance) imaging equipments which is used for scanning purposes.
(b). they are used to detect the brain tumor and defective cells.
(c). they are used to separate the damaged cells from the healthy cells.
(d). they are used in Magneto-hydrodynamic power generation to maintain plasma in the body.

Cryotron:

It is a magnetically operated current switch where the current through one superconducting element can be altered by the magnetic field produced by another superconducting element. Consider a superconducting material (Tantalum-Ta) is surrounded by another superconducting material (Niobium-Nb) and the whole arrangement is placed in a low temperature bath (T <Tc). The critical field of Tantalum–Ta is less than the critical field of Niobium-Nb.

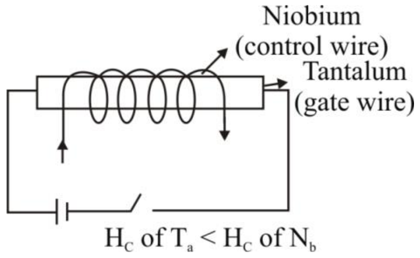


Fig. Cryotron

At an operating temperature, the magnetic field produced by the superconducting material Niobium-Nb may exceed the critical field of Tantalum–Ta. Hence, the superconducting material Tantalum–Ta becomes normal conductor since the critical field of Tantalum–Ta is less than the critical field of Niobium-Nb. But Niobium-Nb will not become normal conductor. Hence, the current in material Ta can be controlled by the current in Niobium-Nb and the system can acts as a relay or switching element.

Magnetic Levitation (MAGLEV):

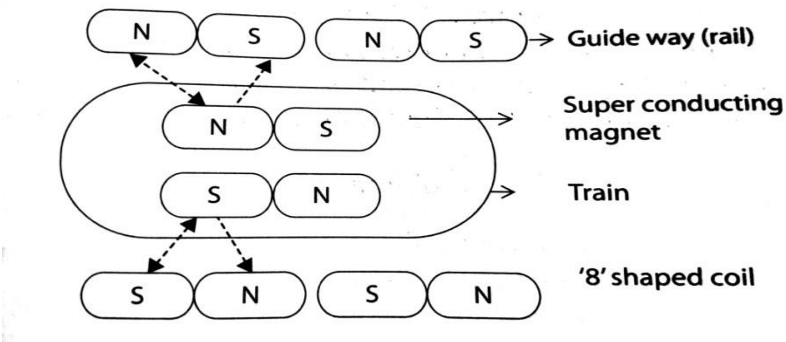


Fig.Magnetic Levitation Train

The most important application of superconductors is maglev or Magnetic Levitation Train. Maglev coaches do not slide over steel rails but float on a 4 inch air cushion over a strongly magnetized track. The principle behind this is electromagnetic forces between the superconducting magnets. This train consists of superconducting magnets placed on each side of the train. It can run in a guide way (rail) which consists of series of "8" shaped coil. Initially the train slide on the rails. When the train moves, the superconducting magnets on each side of the train will induce a current in the "8" shaped coils kept in the guide way. 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 superconducting magnet in the train, while the upper half has the opposite magnetic pole. Hence, the total upward magnetic force acts on the train and the train is levitated or raised above the wheels. Now the train floats in the air. By an alternatively changing the poles of the superconducting magnets 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 superconducting magnets in the train and hence the train is further moved. Because of no mechanical friction, speeds up to 500 Km/hr can be easily achieved.

SQUIDS

SQUIDS means Superconducting Quantum Interference Device and also called Double Junction Quantum Interferometer. It can measure the feeble fields (weak magnetic fields) corresponding to extremely small electric currents generated by heart and brain. The principle behind this is small change in magnetic field produces variation in the flux quantum.

It consists of superconducting ring or loop with “weak link or junction”. Weak link is a thin region which has very low critical current I_c. Weak link acts as a gate, since it allows super current at $I < I_c$ and it blocks super current at $I > I_c$. Weak link is prepared such that it allows only a single fluxon.

Let us consider a superconducting loop with two parallel Josephson junctions and no voltage is applied to the junction. Consider high coherent super current coming along the path 1 is divided along two paths ‘a’ and ‘b’ and again merge into one along the path 2.

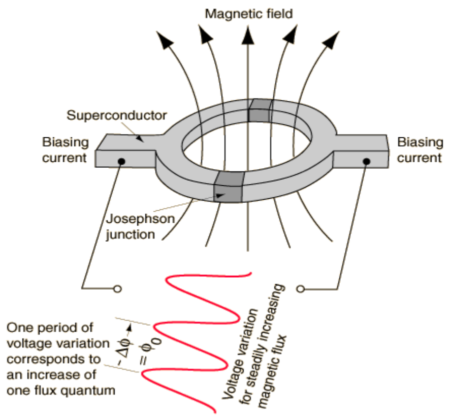


Fig.Superconducting Quantum Interference Device

The super current along the path 1 is represented by a wave function with a phase angle is $I = I_0 \sin\delta_0$

where I_0 is the maximum current and δo is the initial phase angle.

Current along the path a is $I_a = I_0 \sin\delta_a = I_0 \sin[\delta_0 - (\pi\Phi/\Phi_0)]$

Current along the path b is $I_b = I_0 \sin\delta_b = I_0 \sin[\delta_0 + (\pi\Phi/\Phi_0)]$

where δ_a and δ_b are the phase difference between the paths 1&a and 1&b respectively. Φ is the external applied flux. Φ_0 is fluxon.

In the absence of applied magnetic field ($B = 0$), phase difference is zero ($\delta_b - \delta_a = 0$).

In the presence of applied magnetic field ($B \neq 0$), phase difference is not zero

($\delta_b - \delta_a \neq 0$) ($\delta_b - \delta_a = 2\pi\Phi/\Phi o$)

Total current along the path 2 is $I_T = I_a + I_b$

$$= Io \{\sin[\delta_0 - (\pi\Phi/\Phi_0)] + \text{Sin}[\delta_0 + (\pi\Phi/\Phi_0)]\}$$

$$= 2\, I_0 \sin\delta_0 \cos(\pi\Phi/\Phi_0)$$

This equation represents the interference of the two coherent super currents flowing along the paths 1 and 2. I_T varies with $\cos(\pi\Phi/\Phi_0)$ and the condition for current maxima is $(\pi\Phi/\Phi_0) = \pi, 2\pi, 3\pi, 4\pi$, etc. So current maxima occurs by the magnetic flux increases by a fluxon.

In optical interference, light maxima are produced by phase difference (by path difference) between the coherent lights. But in super current interference, current maxima are produced by phase difference (by applied magnetic field difference) between the coherent super currents.The graph shows the typical variation of Ic as a function of magnetic field. Each oscillation corresponds to a fluxon. The quantum interference of super currents permits to count fluxon in a direct way.

When an external weak magnetic field produced by heart or brain is applied perpendicular to the plane of the superconducting ring, current is induced at the Josephson junction and produces interference pattern. The induced current flows around this ring, so that, the magnetic flux in the ring can have quantum values of flux, which corresponds to the value of magnetic field applied.

Applications of SQUID:

1. By measuring the current through the SQUID, one can measure the value of e/h accurately.
2. SQUID is used to detect very tiny magnetic field and hence it is used as a magnetometer.
3. MRI (Magnetic Resonance Imaging) scanning, employing SQUID, is used to measure the field in the micro Tesla region, where as the ordinary MRI is used to measure the field from one to several Tesla.
4. Based on these sensors we have, magnetocardiography (MCA), Magneto encephalography (MEG), etc.
5. They can be used in the finest precision instruments at the forefront of meteorology.
6. A novel application of SQUID is the magnetic marker monitoring method, which is used to trace the path of orally applied drugs.

Supercomputer

A supercomputer is the fastest computer in the world that can process a significant amount of data very quickly. The computing Performance of a “supercomputer” is measured very high as compared to a general purpose computer. The computing Performance of a *supercomputer* is measured in FLOPS (that is floating-point operations per second) instead of MIPS. The supercomputer consists of tens of thousands of processors which can perform billions and trillions of calculations per second, or you can say that supercomputers can deliver up to nearly a hundred quadrillions of FLOPS.

They have evolved from grid to cluster system of massively parallel computing. Cluster system computing means that machine uses multiple processors in one system instead of arrays of separate computers in a network.

These computers are most massive concerning size. A most powerful supercomputer can occupy few feet to hundreds of feet. The supercomputer price is very high, and they can vary from 2 lakh dollar to over 100 million dollars.

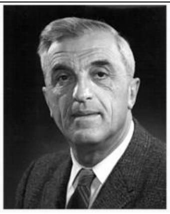
The fastest supercomputer in the world was the Sunway TaihuLight, in the city of Wixu in China which is developed by China’s National Research center of Parallel Computer Engineering & Technology (NRCPC), maintains its number 1 ranking for the first time, with a High-Performance Linpack (HPL) mark of 93.01 peta flops.

Characteristics of Supercomputer

• They can support more than a hundred users at a time.
• These machines are capable of handling the massive amount of calculations that are beyond the human capabilities, i.e., the human is unable to solve such extensive calculations.
• Many individuals can access supercomputers at the same time.
• These are the most expensive computers that can ever be made.
Features of Supercomputer
• They have more than 1 CPU (Central Processing Unit) which contains instructions so that it can interpret instructions and execute arithmetic and logical operations.
• The supercomputer can support extremely high computation speed of CPUs.
• They can operate on pairs of lists of numbers instead of pairs of numbers.
• They were used initially in applications related to national security, nuclear weapon design, and cryptography. But nowadays they are also employed by the aerospace, automotive and petroleum industries.

Uses of Supercomputer

• Supercomputers are not used for everyday tasks because of their superiority.
• Supercomputer handles those applications, which required the real-time processing. The uses are as follows:
• They’re used for scientific simulations and research such as weather forecasting, meteorology, nuclear energy research, physics, and chemistry, as well as for extremely complex animated graphics. They are also used to interpret new diseases and predict illness behavior and treatment.
• The military uses supercomputers for testing new air crafts, tanks, and weapons. They also use them to understand the effect on soldiers and wars. These machines are also used for encrypting the data.
• Scientists use them to test the impact of nuclear weapon detonation.
• Hollywood uses supercomputers for the creation of animations.
• In entertainment, supercomputers are used for online gaming.

 Just to know Dr.FELIXBLOCH (1905-1983) Nobel Prize for Physics (1952)	 HEIKE KAMMERLINGH ONNES
His doctoral thesis established the quantum theory of solids, using Bloch waves to describe electrons in periodic lattices. His additional excellent contributions are nuclear induction and nuclear magnetic resonance, which are the underlying principles of MRI and Magnon.	Dutch scientist Heike Kammerlingh Onnes was awarded the 1913 Nobel Prize in Physics for his work on the properties of matter at low temperatures. He discovered superconductivity

Solved Examples

Problems:

1.A paramagnetic material has a magnetic field intensity of 10^4 A/m. If the susceptibility of the material at room temperature is 3.7×10^{-3}, calculate the magnetization and flux density in the material

Solution

$$\chi = \frac{M}{H} \text{ and } B = \mu_0 (M + H)$$

Hence $M = \chi H$

$$= 3.7 \times 10^{-3} \times 10^4$$
$$= 3.7 \times 10$$
$$= 37\ Am^{-1}$$

Hence magnetization = 37 Am^{-1} (Answer)

Flux density $B = \mu_0 (37 + 10^4)$

$$= (4\Pi \times 10^{-7} \times 10037)$$
$$= (4\Pi \times 10^{-7} \times 10037)$$
$$= 126179.43 \times 10^{-7}$$
$$= 0.0126\ wb/m^2$$

2. A magnetizing field of 1600A/M produces a magnetic flux of 2.4×10^{-5} wb in an iron bar of cross-sectional area 0.2 cm^2. Calculate permeability and susceptibility of a bar.

Solution

We know, magnetic flux

$$\phi_B = BA$$
$$B = \phi_B / B$$

Here ϕ_B = 2.4 × 10^{-5} wb and A = 0.2 cm^2 = 0.2 × 10^{-4} m^2

$$B = \frac{2.4 \times 10^{-5}}{0.2 \times 10^{-4}} = 1.2\, wb/m^2$$

$$= 1.2\, NA^{-1}M^{-1}$$

Magnetic permeability is expressed by the equation

$$\mu = \frac{B}{H}$$

$$\mu = \frac{1.2}{1600} = 7.5 \times 10^{-4}\, NA^{-2}$$

$$\chi_M + 1 = \mu_r = \frac{\mu}{\mu_0}$$

$$\chi_M = \frac{7.5 \times 10^{-4}}{4 \times 3.14 \times 10^{-7}} - 1$$

= 596.13 (Answer)

3.The magnetic susceptibility of a medium is 948 × 10^{-4}. Calculate the permeability and relative permeability.

Solution

$$\mu_r = 1 + \chi_M$$

$$\mu_r = 1 + 948 \times 10^{-11} \approx 1 \text{ or } > 1$$

If μ is the permeability of the medium and μ_0 that of vacuum,

$$\mu_r = \frac{\mu}{\mu_0} \quad or \quad \mu = \mu_r \mu_0$$

$$\mu_0 = 4\Pi \times 10^{-7}$$

$$\mu = 1 \times 4\Pi \times 10^{-7}$$

4.Lead in the superconducting state has critical temperature 6.2 K at zero magnetic field and a critical field 0.064 T. Calculate the critical field at 4 K.

Sol: WKT $H_C = H_0 [1 – (T / T_C)^2]$

Here, we have

H_0 = 0.064 T, T_c = 6.2 K and T = 4 K

$H_c = 0.064 [1 – (4/6.2)^2]$

H_c = 0.037 T

5.The critical values of magnetic field for niobium are 2 x 10^5 A/m and 10^5 A/m at 0 K and 8 K respectively. Determine its critical temperature.

Sol: WKT $H_C = H_0 [1 – (T / T_C)^2]$

Hence $T_C = T / [1 – (H_C / H_0)]^{½}$

Here, we have

H_0 = 2 □ 10^5 A/m, H_C = 10^5 A/m, T = 8 K

$T_C = 8 / [1- (10^5 / 2 \text{ x } 10^5)]^{½}$

T_C = 11.312 K

6.The critical temperature of mercury is 4.153 K for its one isotope of mass 200.59 amu. Calculate the critical temperature of mercury for its another isotope of mass 204 amu.

Sol. WKT $T_c \propto [1 / M^{½}]$

$$(T_{c1}) / (T_{c2}) = (M_2 / M_1)^{½}$$

Here, we have

$T_{c1} = 4.153$ K, $M_1 = 200.59$ amu and $M_2 = 204$ amu

$T_{c2} = (T_{c1}).\ (M_1 / M_2)^{½}$

$T_{c2} = 4.153\ (200.59/204)^{½}$

$T_{c2} = 4.118$ K

7.Determine the critical current that can flow through a long thin superconducting wire of aluminium of diameter 10^{-3} m. The critical magnetic field for aluminium is 7.9 x 10^3 A/m

Sol.

WKT $I_C = 2\pi r H_c$

Here, we have

$H_C = 7.9 * 10^3$ A/m, $2r = 10^{-3}$ m

$I_C = 3.14 * 10^{-3}$ □ 7.9 x 10^3

$I_C = 24.806$ A.

8.Calculate the London penetration depth for lead at 5.2 K if the penetration depth at 0 K is 37 nm. The critical temperature of lead is 7.193 K

Sol.

WKT $(\lambda_T / \lambda_o) = [1 – (T/Tc)^4]^{-1/2}$

Hence, $\lambda_T = \lambda o\ [1 – (T/Tc)^4]^{-1/2}$

Here, we have

$\lambda o = 37$ nm, $T_C = 7.193$ K and $T = 5.2$ K

$\lambda_T = 37\ [\ 1-(\ 5.2/7.193)^4]^{-1/2}$

$\lambda_T = 43.4$ nm.

9.Calculate the superconducting energy gap at T = 0 K predicted by the BCS theory for cadmium. T_c for cadmium is 0.517 K

Sol.

WKT $\Delta = 3.5\ K_B T_c$

Here, we have

$T_C = 0.517$ K, $K_B = 1.38 * 10^{-23}$ J/K

$\Delta = (3.5 * 1.38 * 10^{-23} 8\ 0.517) / 1.6 * 10^{-19}$eV

$\Delta = 1.56 * 10^{-4}$eV

Part-A: Questions

1. What is Bohr Magneton and calculate its value?
2. How will you classify magnetic materials based on permanent dipole moment?
3. Define a diamagnetic material. Give Examples.
4. What is a Paramagnetic material? Give Examples.
5. Define a Ferromagnetic material. Give Examples.

6. Define Curie temperature.
7. What is Neel temperature?
8. What do you mean by Magnetic domain? Write a note on it.
9. What do you mean by Magnetic bubbles?
10. What are the different sources of Permanent Magnetic Moment?
11. What is Curie constant/What is Curie law?
12. State Curie –Weiss law?
13. Write a short on domain theory of Ferromagnetism.
14. Write a note on materials used for Magnetic drum
15. What are the required Magnetic Parameters for recording?
16. Discuss the effect of external Magnetic Field over Magnetic domains?
17. What are the four types of energies involves in the growth of Magnetic domains?
18. Define Magnetic Susceptibility.
19. What is the Magnetic Storage device? Give examples.
20. What is the Floppy disk? Give the salient features of a Floppy disk. What is Magnetic Drum Memory?
21. How does Magnetic Drum Memory Work?
22. Write note on supercomputers?
23. What is Spontaneous magnetisation? Define energy product of a magnetic material. Give its importance in the case of permanent magnets.
24. Define superconductivity.
25. What are superconductors? Define transition temperature of the superconductor.
26. Wriite short note on occurrence of superconductivity.
27. List out some important physical changes in material that occur at T_c.
28. Explain the formation of cooper pair.
29. What is superconducting energy gap?
30. Define coherence length.
31. What do you mean by persistent current?
32. Explain Meissner effect with diagram.
33. Prove that superconductor is a perfect diamagnet.
34. What do you mean by critical magnetic field of a superconductor? How it varies with temperature?
35. What is Silsbee’s rule?
36. Define penetration depth of a superconductor.
37. What is isotope effect?
38. How the entropy of superconductor vary with temperature?
39. Write a note on specific heat capacity of superconductors.
40. Differentiate energy gap of superconductor from semiconductor.
41. What is skin effect?
42. What do you mean by flux quantization?
43. List out the major accomplishments of BCS theory.
44. What is Ginzburg Landau Parameter? Mention its significance.\
45. What is Magnetic levitation and explain the function of Maglev train.
46. What is a cryotron and why it is called so?
47. What is SQUIDS and mention its uses.

Part – B: Questions

1. Explain briefly, different types of Magnetic materials and their properties.
2. Explain Ferromagnetic Domain theory – Weiss theory. And briefly explain different types of energy involved in domain growth with suitable sketches.
3. Describe the construction and working disk? Enumerate the different types of floppy?

   (ii) What are the merits and demerits of the magnetic storage using floppy disk?
4. (i) What is a Magnetic Bubble Memory system?

   (ii) Describe the Formation, Propagation, Read/Write operation and special features of the Magnetic Bubble Memory.
5. Describe the construction and working of Magnetic Hard disk. Give the merits and Demerits of Magnetic Hard Disk.
6. Explain in detail the BCS theory of superconductors.
7. Explain the important properties of superconductors.
8. Write a note on applications of superconductors with reference to cryotron, maglev, SQUIDS and super computers.
9. Write short notes on (i) Meissner effect (ii) Silsbee rule (iii) Isotope effect (iv) Critical magnetic field and (v) Specific heat capacity of superconductors.

.