JESSY

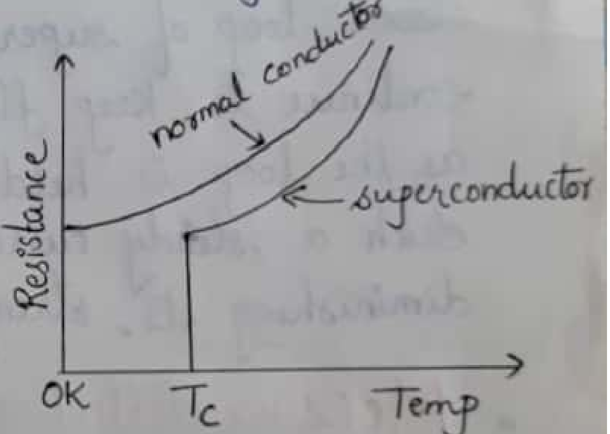
MODULE 5

SUPERCONDUCTORS & SUPERCAPACITORS

(by Kamerling Onnes in 1911)

Superconductivity is the phenomenon in which electrical resistance of material suddenly disappears below a certain temperature. The materials exhibiting superconductivity are called superconductors. The temperature at which the material changes from normal conductor to superconductor is known as Transition temperature or critical temperature.

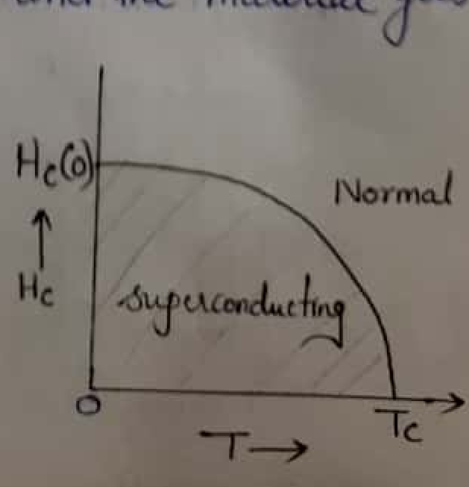
Superconductivity is first observed in mercury, for which critical temp. is 4.2 K.



If $T < T_c \Rightarrow$ Superconductor
$T > T_c \Rightarrow$ normal Conductor

It is further observed that superconductivity vanishes if a sufficiently strong magnetic field is applied. The value of magnetic field at which the superconductivity vanishes is called critical field H_c. When the applied magnetic field exceeds the critical value H_c, the superconducting state is destroyed and the material goes into normal state.

The value of Hc varies with temperature. The critical field decreases progressively with increasing temperature.



(2) The dependence of critical field on temperature is

$$\boxed{H_{c}(T) = H_{c}(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]}$$

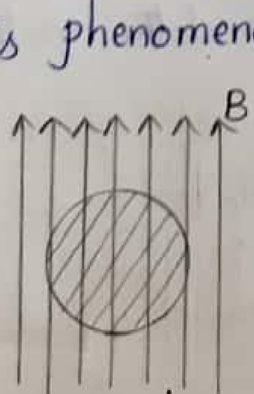
where $H_c(0) \rightarrow$ Critical magnetic field at 0K.
$T_c \rightarrow$ critical temp

Properties of Superconductor

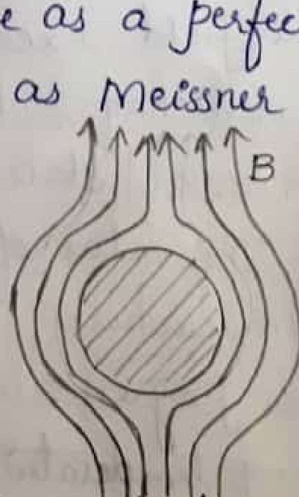
- Zero Electrical resistance :- A superconductor is characterized by zero electrical resistance.
- Persistent current :- Once a current is started in a closed loop of superconducting material, it will continue to keep flowing around the loop, as long as the loop is held below the critical temperature. Such a steady current, which flows without diminishing its strength, is called as persistent current
- Meissner Effect - Perfect Diamagnetism

(by Meissner & Oshsenfeld in 1933)

When a superconductor is cooled below the critical temperature in the presence of a magnetic field, the magnetic flux is expelled from the interior of superconductor, i.e., it behave as a perfect diamagnet. This phenomenon is known as Meissner effect.



Normal
$T > T_c$
or $H > H_c$



Superconducting $T < T_c$
or $H < H_c$

Mathematical Proof for perfect diamagnetism of superconductor

For normal state ($T > T_c$), the magnetic induction inside the specimen is

$$\boxed{B = \mu_0 (H+M)}$$

where $\mu_0 \rightarrow$ permeability in free space
$H \rightarrow$ External magnetic field applied
$M \rightarrow$ magnetisation produced within specimen

As the temperature of specimen is lowered to T_c, the magnetic field is suddenly and completely expelled from it

i.e At $T < T_c$, $B = 0$

$$\therefore \mu_0 (H+M) = 0$$

$$H = -M$$

The susceptibility of the material is $\chi = \frac{M}{H}$

$$\therefore \boxed{\chi = -1}$$

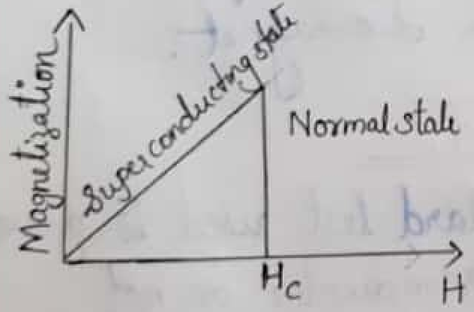
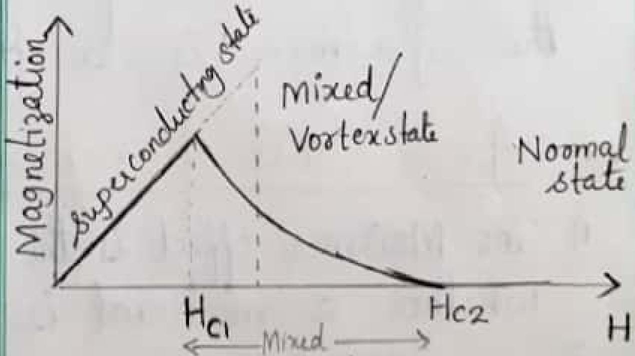
The negative value of magnetic susceptibility shows that the specimen is a perfect diamagnet.

Applications of Meissner Effect

1) The Meissner effect is the standard test used to prove whether a material is superconductor or not.
2) A material in superconducting state is a perfect diamagnet and hence strongly repels external magnets.
A smaller magnet repelled by a bigger superconductor hovers in air. This is known as Levitation effect.
In a similar way, a small chip of superconducting material hangs on to a bigger magnet and this effect is known as suspension effect.
The Levitation effect is utilized in the operation of Maglev trains

Type 1 and Type II Superconductors

Superconductors are divided into Type 1 and Type II depending on the way of transition from superconducting to normal state when external magnetic field is applied.

<table>
<tr><th>Type 1 Superconductor</th><th>Type 2 Superconductor</th></tr>
<tr><td>The superconductors which strictly follow Meissner effect are called Type 1 superconductors
They show perfect diamagnetism</td><td>These superconductors do not follow the Meissner effect strictly.
They do not show perfect diamagnetism</td></tr>
<tr><td>As the applied magnetic field increased beyond critical field H_c, the field penetrates the material completely and transition occurs from superconducting to normal resistive state

</td><td>Here magnetic field penetrates slowly starting from lower critical magnetic field H_{c1} and continues up to upper critical magnetic field H_{c2} at which the material becomes normal conductor

</td></tr>
<tr><td>They have only one critical magnetic field
$H < H_{c}$ → superconducting state
$H > H_c$ → normal state</td><td>They have two critical magnetic fields
$H < H_{c1}$ → superconducting state
$H_{c1} < H < H_{c2}$ → mixed / vortex state
$H > H_{c2}$ → normal state</td></tr>
<tr><td>These are known as soft superconductors ∵ Critical mag. field values are too low ~ 0.1 Tesla</td><td>Known as hard superconductors ∵ Relatively large field is required to bring them back to normal state H_{c2} ~ 30 Tesla.</td></tr>
<tr><td>Applications are limited</td><td>They are used in generating high magnetic fields.</td></tr>
<tr><td>Examples: Lead, Tin, Mercury</td><td>Alloys like Nb–Sn, Nb–Ti, Pb–Bi etc.</td></tr>
</table>

SUPERCAPACITOR

Supercapacitors are high capacity capacitors. A supercapacitor is capable of charging and storing energy at higher density than standard capacitors. The energy storage capacity of a typical capacitor is measured in nano-farads or micro-farads, while that of supercapacitor is in Farads.

Principle of Supercapacitor

Supercapacitors store electrical energy by creating a very thin double layer of electric charge between its plates. Its plates are made up of a porous carbon based material, which soaked in an electrolyte and are separated by a very thin insulator. When the plates are charged up, layers of opposite charges are formed on both sides of the separator, thus forming the double layer. Electrode connected to positive terminal will have negative ions from electrolyte forming a layer. Similarly electrode connected to negative terminal will have positive ions from electrolyte.

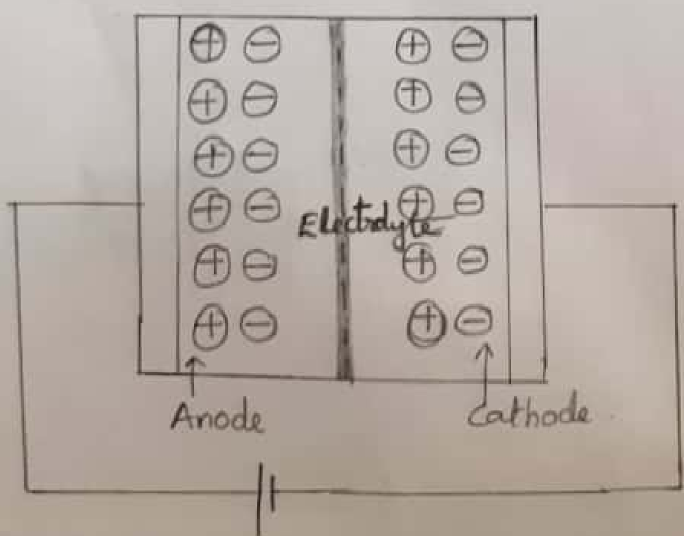


Fig: Construction of supercapacitors

② Types of Supercapacitors

1. Electrostatic double layer capacitors	2. Electrochemical pseudo capacitors	3. Hybrid capacitors eg: Lithium-ions capacitor
They store charge electrostatically with no interaction between electrodes and ions of electrolyte.	They store charge electrochemically through redox reaction by electron charge transfer between electrodes and electrolyte.	They store charge electrostatically and electrochemically. (Combination of 1 and 2)
They use carbon electrodes or derivatives like charcoal powder rods	They use metal oxide or conducting polymer electrodes	It has two electrodes, one that store charge electrostatically and other store electrochemically

Applications of supercapacitors

Supercapacitors can be charged and discharged very quickly. So they are used in applications requiring many rapid charge/discharge.

- As a power source for laptops & flash in cameras
- As a backup power system in missiles
- In start up mechanism of automobiles
- In diesel engine of submarines and tanks, super capacitor act as start up source.
- Hybrid capacitors are extensively used by the military and aerospace engineering for power supplies in laser and high powered radar.
- In energy storage devices for energy harvesting system. (In railway engines, energy while applying brakes is stored in supercapacitors and when acceleration is needed, this energy is provided back to system).

(4) Comparison between supercapacitors & Batteries

Supercapacitor is compared with Lithium-ion battery which is commonly used.

Points	Super capacitor	Lithium-ion battery
1. Charging time	1–10 sec	10–60 min.
2. charging & discharging cycle life	30000 hours	500 hours
3. Cell voltage	2.25 to 2.75 V	3.6 to 3.7 V
4. specific energy (Wh/kg)	typically 5	100 — 200
5. Service life	10–15 years	5–10 years
6. Charging temperature	−40 to 65°c	0 to 45°c
7. Discharging temperature	−40 to 65°c	−20 to 60°c

Best Wishes

Jessy