SUPERCONDUCTIVITY

Q1. Define superconductivity.

(M.U. Dec 2007, 2008, 2009, 2011, 2012, 2016, May 2008, 2010, 2012, 2013, 2014, 2015, 2016) [2 Marks]

When normal metals are cooled their resistivity decreases with temperature. In some materials at a lower temperature resistivity suddenly drops to zero, they are called superconductors.

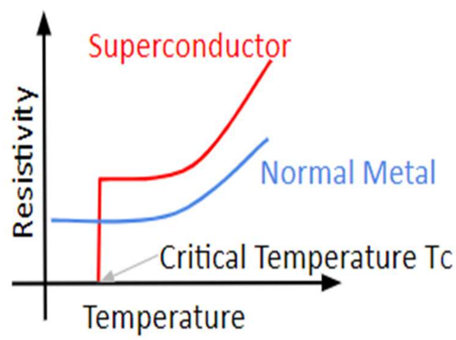


Figure 1: Resistivity Vs temperature

Superconductivity is thus a phenomenon of sudden disappearance of electrical resistance(zero resistance) and expulsion of magnetic flux occurring in certain materials when they are cooled below a characteristic low temperature.

Q2. Define Critical temperature.

(M.U. May 2008, 2010, 2012, 2013, 2016, 2017; Dec. 2007, 2010, 2016) [2 Marks]

When a superconducting material is cooled below a certain temperature, its resistance suddenly drops to zero and it goes into the superconducting state from the normal state. The temperature at which a material transforms into a superconducting state is called **critical temperature 'T_c'** for that material.

Different materials have different critical temperatures. The transition is reversible. When the temperature of the material is increased above the critical temperature, it passes into the normal state. For elementary solids (in extremely pure form), critical temperature (T_c) is found to be very low (e.g. Tungsten = 0.015^o K, Zinc = 0.85^oK, Niobium = 9.46^oK), whereas for compounds or alloys, T_c is found relatively high.

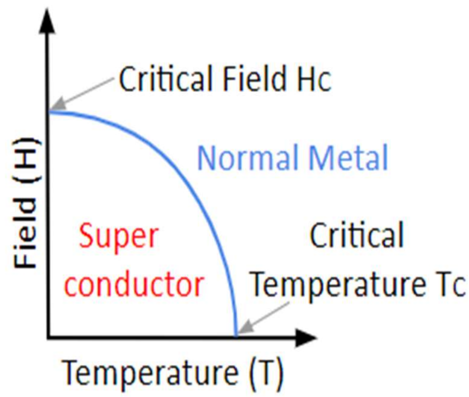


Figure 2: Tc and Hc for Superconductor

{Nb Ti →10^0K, Nb_3Ge→23.2^0K, etc.}

Q3. Define Critical Field.

(M.U. Dec. 2010, 2016) [1 Mark]

A material in its superconducting state, behaves like a diamagnetic material when placed in a weak magnetic field. But if the field strength is increased, the material may lose superconductivity even below critical temperature (T_c).

The critical field (H_c) for a superconducting material is the minimum field value at which normal resistivity is regained by the material and it loses its superconducting state.

Naturally, H_c value depends on the temperature of the superconductor which is placed in an external magnetic field as shown in *Figure 2* and hence it is a function of 'T'. At any temperature 'T' less than T_c, the superconducting material when placed in an external magnetic field, remains superconductor below H_c (T) and becomes normal above the H_c (T). The maximum value of critical field is the field at absolute zero H_0 , critical field at a temperature 'T' in terms of H_0 is given by H_c (T) which is mathematically,

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

For example, pure mercury, $H_c(0) = 0.04$ Tesla --- at $T \approx 0^0K$

$H_c(3) = 0.02$ Tesla --- at $T \approx 3^0K$.

Q4. Explain Meissner Effect with the help of diagrams.

(M.U. May 2008, 2012; Dec. 2012, 2018, 2019; June 2019) [5 Marks]

When a superconductor is in normal state the external magnetic field lines are able to penetrate through its body but when it is in a superconducting state the field lines (i.e. magnetic flux) are strongly expelled from the body. This observation explains a superconductor in a superconducting state is a perfect diamagnetic material. Thus, magnetic flux is excluded by superconducting material, because an equal and opposite magnetization is induced inside its body that opposes the applied field and throws it out.

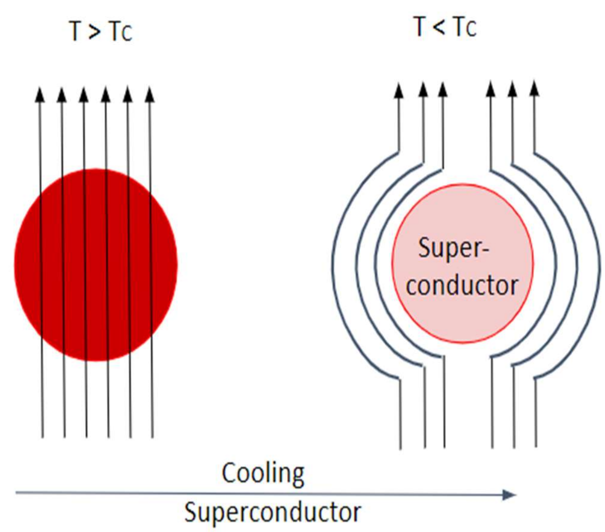


Figure 4: Meissner Effect

When a superconducting material is cooled in a weak magnetic field ($H<H_c$), at a certain low temperature which is the critical temperature (T_c) for that material, the field flux which was penetrating the material before is now suddenly expelled from the body of the superconducting material. The transition from penetration to expulsion due to cooling is shown in *Figure 4*. This phenomenon of sudden flux expulsion is called Meissner's effect. It was discovered by Meissner and Ochsenfeld in 1933. The existence of Meissner's effect is the demonstration of diamagnetic behavior of the superconducting state of the material.

Q5. Enlist applications of Meissner Effect

Thus, Meissner's effect is useful in :

1. **Confirming superconductivity:** When a material being cooled in a weak magnetic field ($H < H_c$) demonstrates flux expulsion, we can confirm that the material has a superconducting behavior. This is because suddenly the magnetic field lines are pushed out of the body which were initially penetrating through the body.
2. **Levitated frictionless bearings:** The machines with rotating shafts ball bearings are covered with lubricants to reduce friction and thereby increase rotations per minute (rpm). With a magnetic shaft and superconducting bearings (or vice versa) the levitation effect will not allow any friction among the surfaces and a high rotation speed can be achieved without any power loss against friction.

Q6. Show that Superconductor is a perfect diamagnet

Susceptibility ($\chi = \frac{M}{H}$) is defined as the magnetization per unit magnetic field. Diamagnetic materials get magnetized in the direction opposite to the applied field and hence the sign of internal magnetization 'M' is opposite to applied field 'H'. This implies that the susceptibility for diamagnetic materials is negative.

The magnetic induction inside a material is given by :

$B=\mu_0 (H+M)$-----(1)

Where, 'H' denotes the external field applied and 'M' denotes the magnetization produced within the specimen.

For superconductor to be in superconducting state at $T < T_C$, flux should be expelled out of the body of the superconductor and hence the net flux inside the body should be zero.

B (inside) = 0 ------(2)

Combining (1) and (2) we get,

$\mu_0 (H+M)=0$

'μ_0' is a non-zero constant and hence,

$H+ M=0$

$M = -H$ --------(3)

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

Thus, the magnetic susceptibility is negative, and hence the superconductor is called a perfect diamagnet.

Q7. What are Type-I and Type-II Superconductors?

(M.U. May 2014, 2015; Dec. 2008 2009, 2011, 2012, 2019) [5 Marks]

Superconductors are classified as Type-I and Type-II superconductors based on their magnetic behavior.

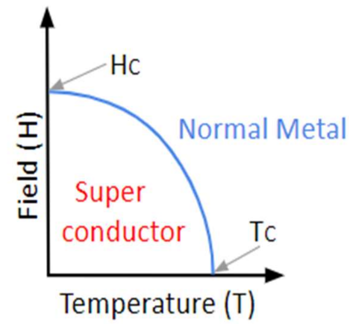
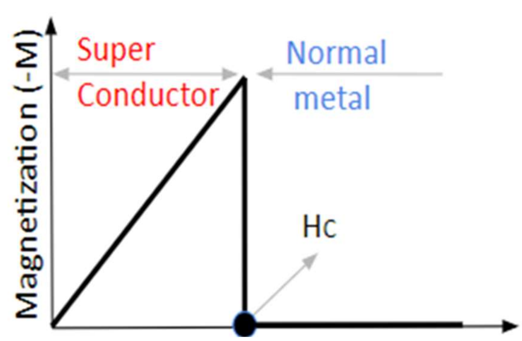


Figure 7a: Field Vs Temperature

Type I superconductors:

- *Figure 4a* shows the plot of magnetic field versus temperature for Type I superconductor indicating the region where the it exists in a superconducting state and the region above critical field (H_C) and critical temperature (T_C) where it enters a normal state.
- Type I superconductors demonstrate a perfect diamagnetic behavior when in their superconducting state
- They get magnetized in the direction opposite to that of the applied field and their magnetization increases with the increase in magnetic field.
- When the applied field is increases beyond the critical field (H_c), they lose superconductivity and also its diamagnetic property thereby entering a normal state.
- Thus at the critical field (H_c), magnetization abruptly drops down to zero and material returns to normal state as shown in *Figure 7b*.
- Type I superconductors generally have a very low value of critical field (H_C ~ 0.05 wb/m^2).



- Due to this they are very susceptible to stray magnetic fields and hence their applications are limited.

Figure 7b: Magnetization Vs Field

Type II superconductors:

- Type-II superconductors are characterized by two critical field values H_{C1} and H_{C2}. *Figure 7c* is a plot of magnetic field versus temperature indicating that the material is in its **superconducting state below** H_{C1}, the superconductor enters its **normal state after** H_{C2}, whereas the superconducting material exists in a **mixed state between** H_{C1} **and** H_{C2}.

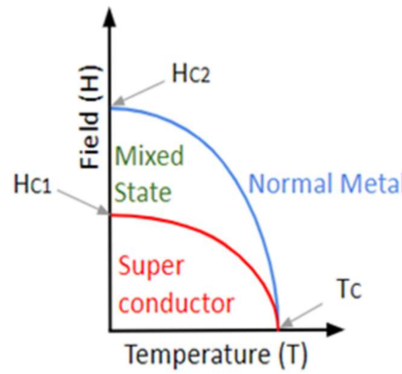


Figure 7c: Field Vs Temperature

- When H_{C1} is crossed, few magnetic field lines penetrate some part of the material, this part gets back to normal state whereas the remaining part of the material is still in the superconducting state. When the applied field reaches value H_{C2} the number of field lines penetrating the body increase in number and occupy the whole body of the superconducting material transforming it into a normal state.
- As shown in *Figure 7d* the magnetization of Type-II superconductor **increases with the increase in applied magnetic field till the lower critical field** H_{C1}.

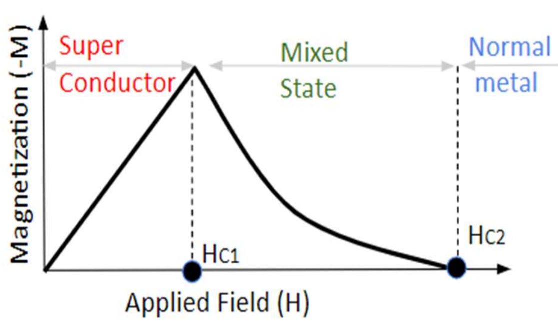


Figure 7d: Magnetization Vs Field (Type-II)

- **After this the magnetization decreases gradually** with increasing applied field, till it reaches zero magnetization at field value H_{C2}.
- In such superconductors the transition from superconducting state to normal state occurs gradually **between H_{C1} and H_{C2}** meanwhile the superconductor remains in the mixed state in which the material is neither in a perfect superconductor nor completely normal.
- Type-II Superconductor provides a liberty of enjoying a partially superconducting state up to H_{C2}, which is relatively larger ($H_{C2} \sim 20$ wb/m^2). Hence, Type-II superconductors are widely used industries.

Q8. Explain properties like energy density and power density. Compare Supercapacitors with batteries and regular capacitors based on these properties.

Energy density is the amount of energy that can be stored per unit mass or per unit volume in any given device which is equivalent to the amount of work the device can perform.

$$W = \frac{1}{2}CV^2$$

Where, W – Energy; C – Capacitance; V – Voltage

This basically means if a device has a high energy density value, then it has the capacity to store a large amount of energy in very small mass or volume or in simple words a small device can do a lot of work. Usually this quantity is measured in **Watt-hours/kilogram (Wh/kg) or Watt-hours/litre (Wh/L).**

Power density is the amount of flow of energy per unit mass or volume, per unit time, in any given device. It gives the measure of how quickly a device can give its energy, relative to its size.

$$P = \left(\frac{1}{4}\right)\frac{V^2}{R}$$

Where, P – Power; V - Voltage applied; R – Internal Resistance

If a device has a high-power density, it can give off large amounts of energy in a very small period of time. It basically tells us numerically, how quickly the stored energy can be utilized. In simple words how quick the work can be done by a device. This quantity is mostly measured in units of kilowatts/kilogram (kW/kg).

Table 8.1: Comparison of various performance parameters for a battery capacitor with supercapacitors

Performance Parameters	Li-ion Battery	Ordinary Capacitor	Supercapacitor
Energy density (Whr/kg)	100-180	0.01-0.02	4-10
Power density (kW/kg)	300-3000	>200	6000-60000
Time to charge	15-60 mins	5-15s	2-10s
Lifespan	5-10 years	15-20 years	10 – 15 years

As shown in the *Table 8.1* Batteries have energy density higher than ordinary capacitors. This means batteries can store more amount of energy, than an ordinary capacitor. Even though Batteries may have a high value of energy density they have a low

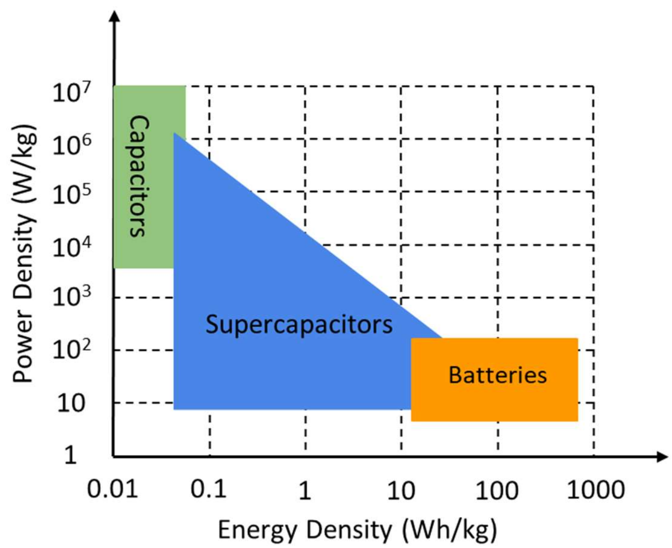


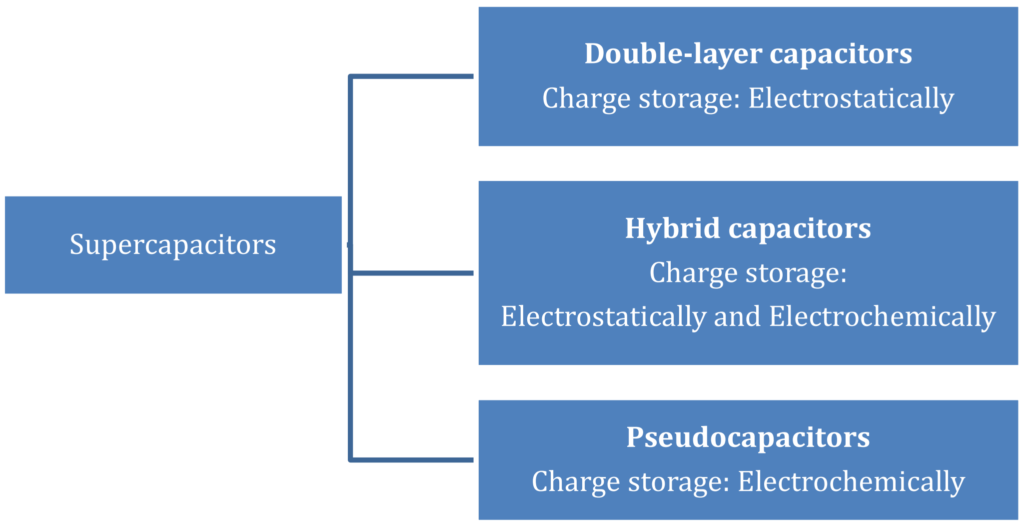
Figure 8: power density vs energy density

power density. This means they cannot output their energy quickly and take a much longer time to re-charge as compared ordinary capacitors that can give off energy and re-charge much more quickly because of their small size. Supercapacitors bridge the gap between the two. They have both, a high-power density, as well as a high energy density. This comparison is also shown in *Figure 8*. They can store and release a large amount of energy as output and are also able to re-charge quickly.

Q9. Explain different types of Supercapacitors.

Supercapacitors are classified as follows:

Table 9.1: Classification of Supercapacitors



1. **Double Layer Capacitors:** These capacitors achieve energy storage with activated carbon electrodes. Thus, we can say that charge storage is done electrostatically.
2. **Pseudo-capacitors:** These capacitors store electrical energy by electron charge transfer between electrodes and electrolyte. Thus, we can say that charge storage is done electrochemically. Metal oxide or conductive polymer electrodes are used.
3. **Hybrid Supercapacitor:** These have two electrodes; one stores charge electrostatically while the other exhibits electrochemical capacitance. Thus, it's a combination of Double layer capacitor and Electrochemical pseudo capacitor and hence named is Hybrid supercapacitors.

Q10. Explain construction and working of a Supercapacitor.

(M.U. Dec. 2019) [5 Marks]

A supercapacitor is a capacitor which has very high capacitance(of the order of Farads) as compared to a normal capacitor (of the order of 10^{-6} Farads). It is capable of **charging and storing energy at a higher density** than normal capacitor. It is also capable of **discharging to use stored energy to do work faster than the normal battery.**

Construction:

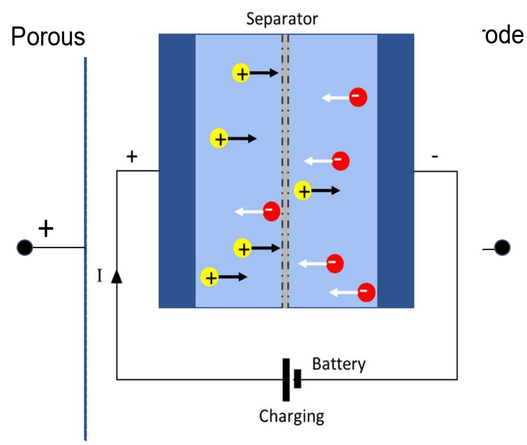


Figure 10a: Supercapacitor construction

A normal capacitor has two plates which are called as its electrodes, Capacitance is directly proportional to the area of plates 'A' and inversely proportional to the distance between the plates 'd'. A **porous substance** used to coat the metallic plates of a supercapacitor due to this the plates of a **supercapacitor have a much larger effective surface area 'A'**. The larger surface area of electrodes which soaked in electrolyte eventually increases the storage capacity for charge. To top this up the space between them 'd' gets **effectively reduced to accommodate the unique insulating separator.** Opposite charges get deposited on either side of the separator, thus creating a double layer of charge as shown in *Figure 10a*. Hence, such capacitors are also called as double layer supercapacitor which is the most commonly used supercapacitor. In this way a Supercapacitor achieves a much higher value of capacitance than any regular capacitor.

Working:

A supercapacitor can be charged and discharged

Figure 10b: Charging

unlimited number of times. When the supercapacitor is not charged, charges in the electrolyte are distributed randomly. In order to charge a supercapacitor, it is connected to a voltage source. While charging positive charges are attracted to the negative terminal and negative charges attracted to the positive terminal as shown in *Figure 10b*. When all the charges are deposited on the electrodes the supercapacitor is said to be fully charged as shown in *Figure 10a*. Once charged the supercapacitor can be connected to a load for discharging as shown in *Figure 10c*.

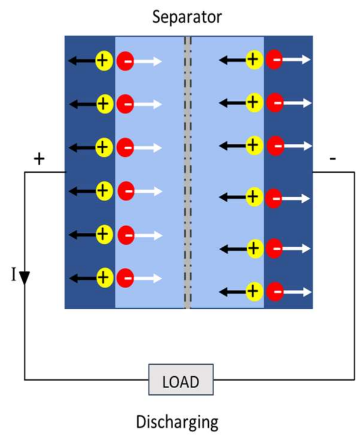


Figure 10c: Discharging

Q8. State the advantages, disadvantages and applications of Supercapacitors.

Advantages of Supercapacitors are:

1. Lasts for a number of years with minimal damage
2. Takes minimum amount of time to charge
3. It is not costly
4. Fast release of battery
5. Stores large amount of energy

Disadvantages of Supercapacitors are:

1. Low voltage for a single cell

2. Energy density is low
3. During discharge complete energy is not used
4. Self - discharge is high
5. Series connection of multiple capacitors is required for high voltage.

Applications of Supercapacitors are:

1. Cellular Devices
2. Uninterruptible Power Supplies (UPS)
3. Industrial Lasers
4. Medical Equipment
5. Wireless communication Systems
6. VCRs, CD Players
7. Security systems, Computer Scanners
8. Microwaves, Coffee Make