Physics of Engineering materials

Course Code: SPH1101

Unit -III: Superconducting Materials

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Superconducting materials have electromagnetic properties, a unique structure, are in a special state of matter, and will have practical applications in the future.
Superconductivity - The phenomenon of losing resistivity when sufficiently cooled to a very low temperature (below a certain critical temperature).

Before the discovery of the superconductors it was thought that the electrical resistance of a conductor becomes zero only at absolute zero. But it was found that in some materials electrical resistance becomes zero when cooled to very low temperatures. These materials are nothing but the SUPERCONDUTORS.

Discovered by Kamerlingh Onnes in 1911 during first low temperature measurements to liquefy helium

Whilst measuring the resistivity of “pure” Hg he noticed that the electrical resistance dropped to zero at 4.2K

In 1912 he found that the resistive state is restored in a magnetic field or at high transport currents
Superconductors

- Superconductivity is a phenomenon in certain materials at extremely low temperatures, characterized by exactly zero electrical resistance and exclusion of the interior magnetic field (i.e. the Meissner effect). This phenomenon is nothing but losing the resistivity absolutely when cooled to sufficient low temperatures.

**Transition Temperature or Critical Temperature ($T_C$)**

- Temperature at which a normal conductor loses its resistivity and becomes a superconductor.
  - Definite for a material
  - Superconducting transition reversible
  - Very good electrical conductors not superconductors eg. Cu, Ag, Au

**Types**

1. Low $T_C$ superconductors
2. High $T_C$ superconductors
The superconducting state is defined by three very important factors: critical temperature ($T_c$), critical field ($H_c$), and critical current density ($J_c$). Each of these parameters is very dependant on the other two properties present

- **critical temperature ($T_c$)** The highest temperature at which superconductivity occurs in a material. Below this transition temperature $T_c$ the resistivity of the material is equal to zero.

- **critical magnetic field ($H_c$)** Above this value of an externally applied magnetic field a superconductor becomes non-superconducting

- **critical current density ($J_c$)** The maximum value of electrical current per unit of cross-sectional area that a superconductor can carry without resistance.
The superconducting elements

Transition temperatures (K) and critical fields are generally low

Metals with the highest conductivities are not superconductors

The magnetic 3d elements are not superconducting

...or so we thought until 2001
## Occurrence of Superconductivity

<table>
<thead>
<tr>
<th>Superconducting Elements</th>
<th>$T_C$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn (Tin)</td>
<td>3.72</td>
</tr>
<tr>
<td>Hg (Mercury)</td>
<td>4.15</td>
</tr>
<tr>
<td>Pb (Lead)</td>
<td>7.19</td>
</tr>
</tbody>
</table>

### Superconducting Compounds

<table>
<thead>
<tr>
<th>Superconducting Compounds</th>
<th>$T_C$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi (Niobium Titanium)</td>
<td>10</td>
</tr>
<tr>
<td>Nb$_3$Sn (Niobium Tin)</td>
<td>18.1</td>
</tr>
</tbody>
</table>
Properties of Superconductors

Electrical Resistance
- Zero Electrical Resistance
- Defining Property
- Critical Temperature
- Quickest test
- $10^{-5}\,\Omega$ cm

Effect of Electric Current
Large electric current – induces magnetic field – destroys superconductivity
Induced Critical Current $i_C = 2\pi r H_C$

Persistent Current
Steady current which flows through a superconducting ring without any decrease in strength even after the removal of the field
Diamagnetic property
Effect of Magnetic Field

- Critical magnetic field \((H_C)\) – Minimum magnetic field required to destroy the superconducting property at any temperature

- The critical field and temperature are interdependent through:

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

- \(H_0\) – Critical field at 0K

\(T\) - Temperature below \(T_C\)

\(T_C\) - Transition Temperature

- This is observed in Type I superconductors, but it can also be used to approximate the behavior of Type II

<table>
<thead>
<tr>
<th>Element</th>
<th>(H_C) at 0K (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>198</td>
</tr>
<tr>
<td>Pb</td>
<td>80.3</td>
</tr>
<tr>
<td>Sn</td>
<td>30.9</td>
</tr>
</tbody>
</table>
**MEISSNER EFFECT:**

- When the superconducting material is placed in a magnetic field under the condition when $T \leq T_C$ and $H \leq H_C$, the flux lines are excluded from the material. The phenomena of expelling magnetic flux experienced by superconductors is called the Meissner Effect.
- The Meissner Effect can be understood as perfect diamagnetism or flux exclusion, where the magnetic moment of the material cancels the external field or $M = -H$.
- Deciding property
  - $\chi = I/H = -1$
- Reversible (flux lines penetrate when $T \uparrow$ from $T_C$)
- Conditions for a material to be a superconductor
  - Resistivity $\rho = 0$
  - Magnetic Induction $B = 0$ when in an uniform magnetic field
- Simultaneous existence of conditions

Comparison of superconductor and standard conductor in a magnetic field. The superconductor excludes itself from the field while the field passes through the conductor.
Magnetic Flux Quantisation
• Magnetic flux enclosed in a superconducting ring = integral multiples of fluxon
• $\Phi = \frac{nh}{2e} = n \Phi_0$ \hspace{1cm} ($\Phi_0 = 2 \times 10^{-15}$ Wb)

Effect of Pressure
• Pressure increases, $T_C$ increases
• High $T_C$ superconductors – High pressure

Thermal Properties
• Entropy & Specific heat decreases at $T_C$
• Disappearance of thermo electric effect at $T_C$
• Thermal conductivity decreases at $T_C$ – Type I superconductors

Stress
• Stress increases, dimension increases, $T_C$ increases, $H_C$ affected

Frequency
• Frequency increases, Zero resistance – modified, $T_C$ not affected
Isotope effect

- $T_C = \text{Constant} / M^\alpha$
- $T_C M^\alpha = \text{Constant (}\alpha - \text{Isotope Effect coefficient)}$
- $\alpha = 0.15 - 0.5$
- $\alpha = 0$ (No isotope effect)
- $T_C \sqrt{M} = \text{constant}$

Impurities
- Magnetic properties affected

Size
- Size $< 10^{-4}$cm – superconducting state modified

General Properties
- No change in crystal structure
- No change in elastic & photo-electric properties
- No change in volume at $T_C$ in the absence of magnetic field
Superconductors can be classified into two types according to their interaction with an external magnetic field:

Type I
- Type I superconductors expel all magnetic flux.
- Superconductivity ends when a critical flux is applied. Examples include mercury, lead, and tin.

Type II
- Type II superconductors, unlike type I, have two critical fields.
- After the first critical field is reached, magnetic flux partially penetrates the material and it enters a state of mixed normal and superconductivity.
- After the second critical flux is passed, superconductivity abruptly ends. Type II superconductors usually have higher critical temperatures.
- Examples include YBCO, vanadium, and BSCCO.
Types of Superconductors - comparison

**Type I**
- Sudden loss of magnetization
- Exhibit Meissner Effect
- One $H_C = 0.1$ Tesla
- No mixed state
- Soft superconductor
- Eg.s – Pb, Sn, Hg

**Type II**
- Gradual loss of magnetization
- Does not exhibit complete Meissner Effect
- Two $H_C$s – $H_{C1}$ & $H_{C2}$ ($\approx 30$ Tesla)
- Mixed state present
- Hard superconductor
- Eg.s – Nb-Sn, Nb-Ti
John Bardeen, Leon Cooper and Bob Schrieffer

“B. C. S.”

Nobel Prize 1972 for their theory of 1957 which explained conventional superconductors: nearly 50 years after their discovery by Kamerlingh Onnes!
Cooper Pairs

each electron in a pair does its own thing ...

(as the Pauli Exclusion Principle says it must)

... but the CENTRES OF MASS of all the pairs do exactly the SAME thing

(all at rest, or all carrying a steady current)

... but what force holds the electrons together?

... and how can we prove they travel in pairs?
The BCS attractive mechanism is due to electrons slightly deforming the crystal lattice. A theoretician would describe this attraction as due to exchange of 'virtual phonons'.

Illustration of cooper pairs moving through a lattice. Cooper pair movement is thought to be the reason superconductivity occurs.

Cooper pair illustrating energy exchange through phonon interaction. A theoretician would describe this attraction as due to exchange of 'virtual phonons'.
Electron phonon attraction
Superconductivity Explained – BCS Theory

- Electron – lattice interaction
- Cooper pairs
- Energy Gap
- Coherence
- Flux Quantization

Phonons!
Superconductivity Explained – BCS Theory

- Electron – lattice interaction
- Cooper pairs
- Energy Gap
- Coherence
- Flux Quantization

Two coupled electrons with opposite momenta and spins
Boson-like
Does not scatter - resistanceless
Energetically favorable in superconducting state
Superconductivity Explained – BCS Theory

- Electron – lattice interaction
- Cooper pairs
- Energy Gap
- Coherence
- Flux Quantization
Superconductivity Explained – BCS Theory

- Electron – lattice interaction
- Cooper pairs
- Energy Gap
- **Coherence**
- Flux
- Quantization

Can calculate phase and amplitude at any point on the wave

Coherence length

One wave equation describes all Cooper pairs:

\[ \Psi_P = \Psi e^{i(P \cdot r)/\hbar} \]
Superconductivity Explained – BCS Theory

- Electron – lattice interaction
- Cooper pairs
- Energy Gap
- Coherence
- Flux Quantization

Magnetic flux around a closed superconducting current loop must be quantized

$$\Phi_0 = \frac{\hbar}{2e} = 2.07 \times 10^{-15} \text{Wb}$$

One fluxon
JOSEPHSON DEVICES

Extraction:

- Principle: persistent current in d.c. voltage

Principle:

- Consists of thin layer of insulating material placed between two superconducting materials.
- Insulator acts as a barrier to the flow of electrons.
- When voltage applied current flowing between superconductors by tunneling effect.
- Quantum tunnelling occurs when a particle moves through a space in a manner forbidden by classical physics, due to the potential barrier involved.
• **Components of current**
  • In relation to the BCS mentioned earlier, pairs of electrons move through this barrier continuing the superconducting current. This is known as the **dc current**.
  • Current component persists only till the external voltage application. This is **ac current**.

• **Uses of Josephson devices**
  • Magnetic Sensors
  • Gradiometers
  • Oscilloscopes
  • Decoders
  • Analogue to Digital converters
  • Oscillators
  • Microwave amplifiers
  • Sensors for biomedical, scientific and defence purposes
  • Digital circuit development for Integrated circuits
  • Microprocessors
  • Random Access Memories (RAMs)
Characterization

• A Josephson junction is made up of two superconductors, separated by a non-superconducting layer so thin that electrons can cross through the insulating barrier.

• The flow of current between the superconductors in the absence of an applied voltage is called a Josephson current.

• The movement of electrons across the barrier is known as Josephson tunneling.

• Two or more junctions joined by superconducting paths form what is called a Josephson interferometer.

• I V curve
High Temperature Superconductors

Characteristics

- High $T_c$
- 1-2-3 Compound
- Perovskite crystal structure
- Direction dependent
- Reactive, brittle
- Oxides of Cu + other elements

1987: Nitrogen limit is overpassed

$\text{YBa}_2\text{Cu}_3\text{O}_{7-x}: \ T_c = 93 \text{ K}$
• Yttrium Barium Copper Oxide was the first superconductor developed with a $T_c$ above the boiling point of Nitrogen ($T_c$=90 K).

• Thallium Barium Calcium Copper Oxide has the highest $T_c$ out of all superconductors ($T_c$=125 K)

• Copper Oxides are believed to be good superconductors partly due to the Jahn-Teller effect, which causes the 2 oxygens on opposite sites of the octahedron to be farther from the copper than the other 4 oxygens of the octahedron.

• This suggests that the electrons interact strongly with the positions of copper and oxygen in the lattice (Cooper pair).

• Antiferromagnetism must be eliminated for superconductivity to appear.
Applications of Superconductors

• Transmission of power
• Switching devices
• Sensitive electrical instruments
• Memory (or) storage element in computers.
• Manufacture of electrical generators and transformers
• Nuclear Magnetic Resonance (NMR)
• Diagnosis of brain tumor
• Magneto – hydrodynamic power generation
Cryotron

The cryotron is a switch that operates using superconductivity. The cryotron works on the principle that magnetic fields destroy superconductivity. The cryotron is a piece of tantalum wrapped with a coil of niobium placed in a liquid helium bath. When the current flows through the tantalum wire it is superconducting, but when a current flows through the niobium a magnetic field is produced. This destroys the superconductivity which makes the current slow down or stop.
Magnetic Levitated Train

**Principle:** Electro-magnetic induction

Magnetic levitation transport, or maglev, is a form of transportation that suspends, guides and propels vehicles via electromagnetic force. This method can be faster than wheeled mass transit systems, potentially reaching velocities comparable to turboprop and jet aircraft (500 to 580 km/h).

Superconductors may be considered perfect diamagnets \((\mu_r = 0)\), completely expelling magnetic fields due to the Meissner effect. The levitation of the magnet is stabilized due to flux pinning within the superconductor. This principle is exploited by EDS (electrodynamic suspension) magnetic levitation trains.
In trains where the weight of the large electromagnet is a major design issue (a very strong magnetic field is required to levitate a massive train) superconductors are used for the electromagnet, since they can produce a stronger magnetic field for the same weight.

**Electrodynamtic suspension**: In Electrodynamtic suspension (EDS), both the rail and the train exert a magnetic field, and the train is levitated by the repulsive force between these magnetic fields. The magnetic field in the train is produced by either electromagnets or by an array of permanent magnets. The repulsive force in the track is created by an induced magnetic field in wires or other conducting strips in the track.

At slow speeds, the current induced in these coils and the resultant magnetic flux is not large enough to support the weight of the train. For this reason the train must have wheels or some other form of landing gear to support the train until it reaches a speed that can sustain levitation.
Propulsion coils on the guideway are used to exert a force on the magnets in the train and make the train move forwards. The propulsion coils that exert a force on the train are effectively a linear motor: An alternating current flowing through the coils generates a continuously varying magnetic field that moves forward along the track. The frequency of the alternating current is synchronized to match the speed of the train. The offset between the field exerted by magnets on the train and the applied field create a force moving the train forward.

**Advantages**

- No need of initial energy in case of magnets for low speeds, One litre of liquid nitrogen costs less than one litre of mineral water
- Onboard magnets and large margin between rail and train enable highest recorded train speeds (581 km/h) and heavy load capacity. Successful operations using high temperature superconductors in its onboard magnets, cooled with inexpensive liquid nitrogen
- Magnetic fields inside and outside the vehicle are insignificant; proven, commercially available technology that can attain very high speeds (500 km/h); no wheels or secondary propulsion system needed
- Free of friction as it is “Levitating”
SQUIDS - (Super conducting Quantum Interference Devices)

How it works

Phase change due to external magnetic field → Current flow → Voltage change

\[ \Delta \phi(B) + 2\Delta \phi(i) = n2\pi \]

Due to B field → Due to junctions → Must be quantized
Principle:

*Small change in magnetic field, produces variation in the flux quantum.*

Construction:

The superconducting quantum interference device (SQUID) consists of two superconductors separated by thin insulating layers to form two parallel Josephson junctions.

- **Explanation:**
  - When the magnetic field is applied perpendicular to the ring, current is induced at the two junctions.
  - Induced current flows around the ring thereby magnetic flux in the ring has quantum value of field applied.
  - Therefore used to detect the variation of very minute magnetic signals.

Types of SQUID

Two main types of SQUID:

1) RF SQUIDs have only one Josephson junction.
2) DC SQUIDs have two or more junctions.

Thereby, more difficult and expensive to produce, much more sensitive.
The dream - “Tomorrow’s Superconducting World”

Energy Saving: power lines, electric motors, transformers

Medical Diagnostics: Magnetic Resonance Imaging, SQUID: Brain activity, Heart function

Computing: 1000 times faster supercomputers

Information Technology: much faster, wider band communications

Underground rapid transit: Heathrow to Gatwick in 10 minutes

Cargo-carrying submarines, all-electric US Navy

350 mph levitated Intercity trains

magnetically launched space shuttle
Some of these dreams are already reality...

SQUID measurement of neuro-magnetic signals

Japanese levitating train has superconducting magnets onboard

Superconducting power cable installed in Denmark

(nuclear) magnetic resonance imaging of the brain, in the field from a superconducting magnet
1. Define superconductivity.
2. What are superconductors?
3. Define transition temperature of the superconductor.
5. List out some important physical changes in material that occur at $T_c$.
6. Explain the formation of cooper pair.
7. What is superconducting energy gap?
8. Define coherence length.
9. What do you mean by persistent current?
10. Explain Meissner effect with diagram.
11. Prove that superconductor is a perfect diamagnet.
12. What do you mean by critical magnetic field of a superconductor? How it varies with temperature?
13. What is Silsbee’s rule?
15. What is isotope effect?
16. How the entropy of superconductor vary with temperature?
17. Write a note on specific heat capacity of superconductors.
18. Differentiate energy gap of superconductor from semiconductor.
PART-A: QUESTIONS (contd...)

19. What is skin effect?
20. What do you mean by flux quantization?
21. List out the major accomplishments of BCS theory.
22. Differentiate Type I and Type II superconductors.
24. What is the effect of pressure on materials?
25. How can you generate microwaves using Josephson device?
26. Explain I - V characteristics of Josephson current?
27. What is a Josephson device? Explain with diagram.
28. Explain DC and AC Josephson effects.
29. List out applications of Josephson’s device.
30. What are high temperature superconductors? Give examples.
31. What are high $T_c$ and low $T_c$ superconductors? Differentiate them.
32. What is Magnetic levitation and explain the function of Maglev train.
33. Define fluxon and fluxoid.
34. What is a cryotron and why it is called so?
35. What is SQUIDS and mention its uses.
PART – B: QUESTIONS

1. Explain in detail the BCS theory of superconductors.
2. Explain type I and type II superconductors with graphs and write the differences between them.
3. Explain the important properties of superconductors.
4. Write short notes on high $T_c$ superconductors.
5. Write a note on applications of superconductors with reference to cryotron, maglev and SQUIDS.
6. Write short notes on (i) Meissner effect (ii) Silsbee rule (iii) Isotope effect (iv) Critical magnetic field and (v) Specific heat capacity of superconductors.