

Chapter-40

Phenomenon, Properties and Applications of Superconducting Materials

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Abstract:

This chapter of superconductivity, a phenomenon in which certain materials can conduct electricity with no resistance. It provides an overview of the history of superconductivity research, the current state of the field, and the potential applications of superconductivity. It discusses the different types of superconductors, their properties, and the challenges associated with their use. It also explores the various theories that have been proposed to explain the phenomenon of superconductivity, as well as the potential for future research.

1. Introduction:

Superconductivity is a quantum mechanical phenomenon characterized by the complete disappearance of electrical resistance and the expulsion of magnetic fields from a material when cooled below a certain critical temperature (T_c). This remarkable behaviour was first discovered in 1911 by Dutch physicist Kamerlingh Onne's during experiments on the electrical conductivity of mercury at low temperatures. Upon reaching a temperature of $4.2\text{ }^0\text{K}$, the resistivity of mercury abruptly dropped to zero, a finding that defied the classical understanding of conduction and laid the foundation for a new field in condensed matter physics. Superconductors have the potential to revolutionize modern technology due to their ability to transport electricity without energy loss. This property makes them highly suitable for applications in power transmission, magnetic levitation, high-field magnets, and emerging areas such as quantum computing. Despite of their potential, practical utilization of superconductors is often limited by the requirement for extremely low operating temperatures and complex material synthesis processes.

2. Historical Development:

According to Kamerlingh Onne's discovery, superconductivity was observed in several other elements including tin and lead. In the mid-20th century, theoretical developments led to the formulation of the London equations and the Ginzburg-Landau theory, providing macroscopic descriptions of superconducting behaviour. The most significant theoretical milestone came in 1957 with the Bardeen-Cooper-Schrieffer (BCS) theory, which explained superconductivity in terms of electron pairing mediated by phonons. A major breakthrough occurred in 1986 when Bednorz and Müller discovered superconductivity in a lanthanum-based copper oxide ceramic (LaBaCuO), with a T_c of approximately $35\text{ }^0\text{K}$. This discovery marked the advent of high-temperature

superconductivity (HTS), and subsequent research led to materials such as $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO), with T_c values above $90\text{ }^\circ\text{K}$, enabling the use of liquid nitrogen as a coolant.

3. Fundamental Properties of Superconductors:

3.1 Zero Electrical Resistance

The hallmark of superconductivity is the complete absence of electrical resistance. Below the critical temperature, electrons form Cooper pairs that move through the crystal lattice without scattering. As a result, an electrical current can circulate indefinitely in a superconducting loop without any applied voltage.

3.2 Meissner Effect

The Meissner effect, discovered in 1933 by Meissner and Ochsenfeld, refers to the expulsion of magnetic flux from a superconductor when it transitions into the superconducting state. This effect distinguishes superconductors from perfect conductors and is a direct consequence of their thermodynamic phase transition.

3.3 Critical Parameters

Superconductors are characterized by three critical parameters:

- **Critical Temperature (T_c):** The temperature below which superconductivity occurs.
- **Critical Magnetic Field (H_c):** The maximum external magnetic field a superconductor can withstand before transitioning to the normal state.
- **Critical Current Density (J_c):** The maximum current density that a superconductor can carry without resistance.

3.4 Flux Quantization

In superconducting loops, magnetic flux is quantized in discrete units. This phenomenon, known as flux quantization, is a direct result of the macroscopic quantum coherence in superconductors.

3.5 Josephson Effects

The Josephson effect occurs when two superconductors are separated by a thin insulating layer, allowing for the tunnelling of Cooper pairs. This gives rise to the DC and AC Josephson effects, which are foundational for superconducting electronics, quantum interference devices (SQUIDS), and voltage standards.

4. Classification of Superconductors:

Based on Magnetic Response

Type I Superconductors:

- Exhibit a sharp transition into the superconducting state.
- Show complete magnetic flux expulsion (perfect Meissner effect).
- Have a single critical magnetic field (H_c).
- Examples: Mercury (Hg), Lead (Pb), Aluminium (Al).

Type II Superconductors:

- Allow partial magnetic field penetration through quantized vortices between lower (H_{c1}) and upper (H_{c2}) critical fields.
- Show a mixed state with superconducting and normal regions.
- Examples: Niobium-Titanium (NbTi), $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO).

Based on Material Composition

Elemental Superconductors

- Pure metallic elements that exhibit superconductivity.
- Typically, low T_c values.
- Examples: Tin (Sn), Zinc (Zn), Niobium (Nb).

Alloy and Intermetallic Superconductors

- Engineered to enhance performance characteristics.
- Common in applications requiring strong magnetic fields.
- Examples: NbTi, Nb₃Sn.

High-Temperature Superconductors (HTS)

- Cuprate-based ceramic materials with $T_c > 77$ °K.
- Complex crystal structures with copper-oxygen planes.
- Examples: YBCO, BSCCO (Bi₂Sr₂CaCu₂O₈).

Iron-Based Superconductors

- Composed of iron and chalcogen elements.
- Exhibit unconventional pairing mechanisms.
- Examples: LaOFeAs, FeSe.

Organic and Carbon-Based Superconductors

- Include charge-transfer salts and doped fullerenes.
- Generally have low T_c .
- Examples: (TMTSF)₂PF₆, K₃C₆.

5. Theoretical Framework:

5.1 BCS Theory

The BCS theory describes the microscopic origin of superconductivity in conventional materials. It proposes that electrons form Cooper pairs through attractive interactions mediated by lattice vibrations (phonons). These pairs condense into a single quantum state with zero resistance.

The theory accounts for energy gap formation, isotope effect, and critical temperature dependence.

5.2 Ginzburg-Landau Theory

A phenomenological approach that introduces a complex order parameter representing the superconducting wavefunction. It explains magnetic field penetration depth and coherence length, providing insight into Type I and Type II behaviours.

5.3 London Equations

These equations describe the electromagnetic response of superconductors, including the exponential decay of magnetic fields within the material (London penetration depth).

5.4 Unconventional Superconductivity

In high- T_c and some heavy fermion materials, electron pairing is not mediated by phonons. The pairing symmetry (e.g., d-wave) and mechanism (e.g., spin fluctuations) differ significantly from conventional superconductors.

6. Synthesis and Processing:

6.1 Synthesis Techniques

- **Solid-State Reaction:** Common for bulk HTS materials; involves calcination and sintering at high temperatures.
- **Pulsed Laser Deposition (PLD):** Used for high-quality thin films.
- **Chemical Vapor Deposition (CVD):** Enables controlled film growth.
- **Melt Texturing:** Improves grain alignment in bulk ceramics.

6.2 Processing Challenges

- Achieving phase purity and stoichiometry.
- Controlling oxygen content in cuprates.
- Enhancing mechanical properties and grain connectivity.

7. Characterization Techniques:

- **X-ray Diffraction (XRD):** Identifies crystal structure and phase purity.
- **Scanning Electron Microscopy (SEM):** Examines surface morphology.
- **Four Probe Method:** Measures resistivity and determines Critical Temperature T_c .
- **Magnetization (VSM/SQUID):** Measures critical fields and magnetic behaviour.
- **AC Susceptibility:** Detects onset of superconductivity and flux dynamics.

Advantages of Superconductors:

Superconductors have the following advantages

1. Transforming the Electricity Grid:

The electricity grid is being transformed by superconductor technology, which offers lossless wires and cables that raises the system's dependability and effectiveness. The current electrical system will be replaced by a superconducting grid by 2030, according to plans. In contrast to modern grid lines, a superconducting power system takes up less space and is buried in the earth.

2. Improving Wide-Band Telecommunication:

Cell phone effectiveness and dependability can be greatly increased by using wide-band telecommunications technology, which works best at gigahertz frequencies. Circuitry built on semiconductors has a very difficult time producing such frequencies. However, Hypres's superconductor-based receiver, which employs a technique known as rapid single flux quantum, or RSFQ, integrated circuit receiver, has successfully accomplished them. It uses a 4-kelvin cryocooler to function. Many mobile phone receiver transmitter towers now using this technology.

3. Aiding Medical Diagnosis:

Strong superconducting magnets are used in magnetic resonance imaging (MRI) to create broad, homogenous magnetic fields inside the patient's body.

8. Applications of Superconductors:

8.1 Medical Imaging

Superconducting magnets are integral to MRI systems, providing stable and intense magnetic fields with minimal energy consumption.

8.2 Power Transmission and Storage

Superconducting cables and fault current limiters offer efficient energy transport and grid protection.

8.3 Transportation

Trains utilize the Meissner effect for frictionless travel. Projects in Japan and China have demonstrated practical implementation.

8.4 Particle Accelerators

Superconducting radio-frequency (SRF) cavities enhance particle acceleration efficiency in research facilities like CERN.

8.5 Quantum Computing

Superconducting qubits, based on Josephson junctions, form the foundation for several quantum computing platforms.

8.6 Magnetic Energy Storage

Superconducting Magnetic Energy Storage (SMES) systems provide fast-response energy reserves in power grids.

9. Challenges and Future Perspectives:

Challenges are

- **Cooling Requirements:** Most superconductors require cryogenic temperatures.
- **Material Brittleness:** HTS ceramics are mechanically fragile.
- **Fabrication Costs:** Complex synthesis and processing increase costs.

Future research aims to

- Discover room-temperature superconductors.
- Develop flexible and wire-shaped HTS conductors.
- Integrate superconductors with semiconductors for hybrid devices.
- Explore topological superconductivity for robust quantum computing.

10. Conclusion:

Superconducting materials represent a pinnacle of condensed matter research with wide-ranging applications in modern technology. The field has evolved from elemental superconductors to complex oxide ceramics and beyond, with each generation offering higher performance and broader applicability. While practical implementation is still constrained by material and economic factors, ongoing research holds the promise of overcoming these limitations and realizing the full potential of superconductivity in the 21st century.

11. References:

1. Tinkham, M. Introduction to Superconductivity (2nd ed.) Dover Publications. (2004).
2. Poole, C. P., Farach, H. A., Creswick, R. J., & Prozorov, R. Superconductivity. Academic Press. (2014).
3. Buckel, W., & Kleiner, R. Superconductivity: Fundamentals and Applications. Wiley-VCH. (2019).

4. Gurevich, A. *Superconducting Materials: Advances in Technology and Applications*. Springer. (2020).
5. Gao, Y., et al. "Recent advances in room-temperature superconductivity research." *Nature Reviews Materials*, 8, 291–308. (2023).
6. Hirsch, J. E., Maple, M. B., & Marsiglio, F. "Superconducting materials classes: Introduction and overview." *Physica C: Superconductivity and its Applications*, 514, 1–8. (2015).
7. Mukhanov, O. A., Semenov, V. K., & Likharev, K. K. "Superconductor digital electronics: Current status and future prospects." *IEEE Transactions on Applied Superconductivity*, 29(5), 1300510. (2019).