Proceedings of the 4th International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/80/2025.GL19718

Basic Theory and Application Analysis of Superconducting Technology

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Abstract: With the progress of the times, the effective use of energy is becoming more and more important. Among a lot of energy sources, electric energy is currently the most widely used. However, the thermal effect of conventional conductors affects the efficient use of electrical energy. But the superconducting phenomenon presents a solution to this problem. This paper first introduces the phenomenon of superconductivity, the history of research on superconductivity, and the classification of superconducting materials, and explores the potential applications of superconducting materials in various fields. The role of computer science is particularly prominent. The application of superconducting technology has made quantum computers possible, and more efficient storage has also increased the scope of application of superconducting technology. In addition, superconducting technology also makes energy transmission more efficient. Finally, this article proposes the challenges and prospects facing the development of superconducting technology, among which the working temperature is the primary problem to be overcome.

Keywords: Superconductive, Quantum, Efficient storage

1. Introduction

With the progress of the times and development of science and technology, the effective utilization of electrical energy is becoming increasingly important. Hence, the negative impact of electric resistance and heating cannot be ignored. But the advent of superconductivity technology has made it possible to resolve this matter [1]. Superconducting technology can solve the problem of inefficiency caused by cable heating in power transportation, and can provide an environment for quantum computers. No matter what kind of problem, the emergence and application of superconducting technology will be meaningful to human beings and society.

This paper first introduces the definition of the superconducting phenomenon, the history and the variety of superconducting materials [2]. Secondly, it explains the possible role of superconducting technology in the field of computer, power transmission and transportation respectively. Finally, the challenges and prospects in the research process and in the future are described.

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2. Basis of superconducting technology

2.1. Definition of the superconducting phenomenon

Superconductivity usually refers to the superconducting state, which refers to some conductors that reduces the resistance to nearly zero at low temperature and small magnetic fields, while showing complete diamagnetic resistance. The superconducting state has several critical properties, for example the critical temperature, the critical magnetic field , and the critical current density. The conductor must be below all critical parameters at the same time for the conductor to maintain superconductivity. Once the physical quantity of the conductor exceeds the critical properties, the superconducting state will be disappeared and changed back to the normal state, no longer having superconductivity and diamagnetism. With this feature, the application of superconducting technology in power systems can greatly reduce power loss and thus reduce fuel consumption. In addition, superconducting technology can also be used to develop new electronic devices and explore new medical directions.

2.2. Research history of superconducting phenomenon

The history of superconductivity began in 1911 with Dutch physicist Heike Kamerlingh Onnes). In 1908, Ones successfully liquefied helium, creating conditions for the study of material properties at extremely low temperatures [3]. In 1911, he measured the resistance of pure mercury at low temperatures, and found that when the temperature dropped to 4.2K (-268.95℃), the resistance of mercury suddenly disappeared, a phenomenon called superconductivity.

In 1933, German physicists Walter Meissner and Robert Oxenfeld independently discovered another fundamental property of the superconductor, —full diamagnetism, namely the Meissner effect. They found that superconductors in weak magnetic fields were able to repel magnetic fields from the inside.

In 1935, the London brothers proposed the London equation, which describes the relationship between the superconducting current and the electric and magnetic field, and explains the zero resistance and the Meissner effect (complete diamagnetism). The London equation combines with Maxwell's equations to form the basic equation for superconducting electrodynamics.

In 1950, Vitaly Ginzburg and Leo Landau proposed the Ginzburg-Landau equation (G-L equation) based on Landau's second-order phase transition theory. The theory introduces the concept of an order parameter to describe some ordering of the superconducting electron density, revealing that the superconductor has a macroscopic quantum effect.

In 1957, John Badin, Leon Cooper, and Robert Schriver proposed the BCS theory that successfully explained the superconductivity of conventional metals and alloys. The BCS theory suggests that "electrons" with equal momentum direction form spin-singlet pairs by exchanging virtual phonons, and these paired electrons form Cooper pairs. In the framework of the BCS theory, superconductivity is a macroscopic effect resulting from condensing Cooper pairs. The development is shown in Figure 1.

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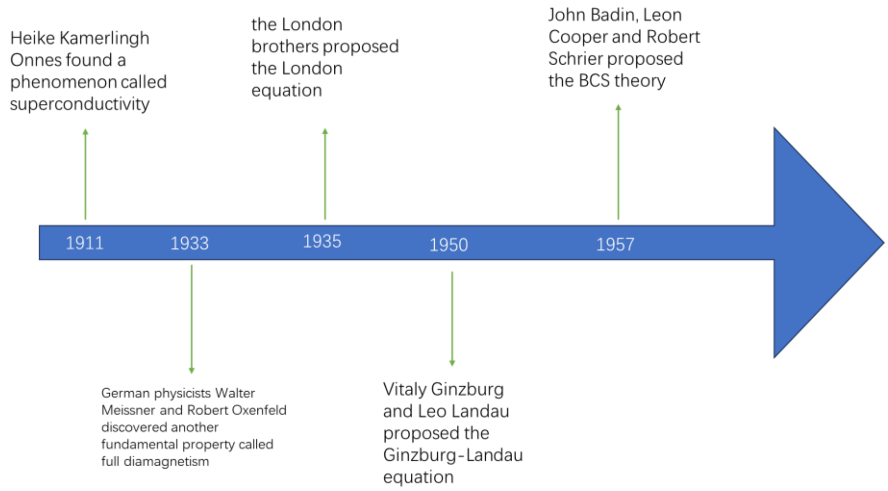

Figure 1: History of superconducting phenomenon

2.3. Classification of superconducting materials

When superconductors are discovered, they are attracted by their peculiar properties (namely, zero resistance, diamagnetism, and quantum tunneling) [4]. But for 75 years, all discovered superconductors showed superconductivity at extremely low temperatures (23 K), so their application was greatly limited. However, with the study of old materials and the discovery of new materials, people have found that materials that can also have superconductivity at relatively high temperatures, called high-temperature superconductors, while the previous materials that have superconductivity at very low temperatures are called low-temperature superconductors. A low-temperature superconductor is a conductor that exhibits superconductivity at the critical temperature below 25K (-248 degrees Celsius).

In 1986, German physicists Beroz and Muer discovered the 35K superconducting lanthanum barium copper oxygen system. The breakthrough discovery led to a number of rare earth barium copper oxide superconductors at higher temperatures. In early 1987, Zhu Jingwu from the United States and Zhao Zhongxian from the Chinese Institute of Physics discovered the 90K yttrium-barium-copper-oxygen superconductor by element exchange, thus achieving the first breakthrough of the temperature barrier at the temperature of liquid nitrogen (77 K). Bonoz and Müller also received the 1987 Nobel Prize in Physics for their groundbreaking work. These superconductors are often referred to as high-temperature superconductors because their critical temperature exceeds the temperature of liquid nitrogen (77 K). In late 1987, Shen Junru, a Chinese scholar studying in the United States, first discovered the first thallium-barium-copper-oxygen high-temperature superconductor without rare earths. In early 1988, Japan developed a bismuth-strontium-calcium-copper-oxygen superconductor with a critical temperature of 110 K. In February 1988, Shen Zhenyi also discovered the 125K thallium-barium-calcium-copper-oxygen superconductor. A year later, French scientists discovered a 135K mercury-barium-calcium-copper-oxygen superconductor.

On the 12th in July 2023, the journal "Nature" published the first discovery of a nickel oxide superconductor in the temperature range of liquid nitrogen, led by the team of Professor Wang Meng from Sun Mountain University. This is the first new high-temperature superconducting system discovered by Chinese scientists worldwide, and the second unconventional superconducting material discovered by humans in the temperature range of liquid nitrogen. High-temperature superconductors include four categories: 90K rare earths, 110K bismuth, 125K thallium and 135K mercury. Both contain copper and oxygen and are therefore also referred to as copper-oxygen superconductors. They have a similar layer crystal structure, the copper-oxygen layer being a superconducting layer.

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3. Application scenario analysis of superconducting technology

3.1. The role of superconducting technology in the computer field

The zero-resistance characteristics of superconductors make superconducting computers more advantageous in processing large amounts of data and complex operations, which can greatly improve the computational efficiency. Superconducting technology is one of the most important ways to realize the quantum computer. Quantum computers use the characteristics of superposition and entanglement of qubits, and have the ability to process large amounts of information in parallel, and the computing speed is far faster than that of traditional computers. Superconducting materials have no resistance under certain conditions, and therefore do not produce energy loss when transmitting the current. This allows superconducting computers to significantly reduce power consumption during operation. For large-scale data centers and high-performance computer clusters, energy costs can be effectively reduced.

The characteristics of superconducting materials make them also have the application potential in the memory field. For example, properties such as the magnetic flux pinning effect of superconducting materials or the Josephson junction of superconducting materials can be exploited to create high-density, low-power memory. This memory can not only improve the storage density of data, but also enhance the stability and reliability of data and reduce the risk of data loss.

At present, Wu Chunwang and other scholars have studied the physical basis of superconducting quantum computing, the realization of fast quantum phase gate based on Circuit QED structure, cluster state quantum computing based on superconducting system, and the simulation of interaction Bose system using superconducting microcavity array [5]. The study of this paper promotes the experimental realization of the superconducting quantum computer. Zhang Liang and other scholars studied the design and test of single-stage amplification interface circuit and two-stage amplification interface circuit in superconducting state [6].

3.2. The role of superconducting technology in the energy transmission

The superconducting materials have no resistance in the superconducting state, indicating that the current can flow without resistance, which greatly improves the efficiency of energy transmission. However, due to the high electrical conductivity of the superconducting materials, it can support a greater current density, allowing more electricity to be transmitted in the same cross-sectional area.

In the traditional power transmission mode, due to the thermal effect of the resistance of the wire, part of the energy will be lost in the form of heat. And superconducting cables can significantly reduce this energy loss due to their zero-resistance properties.

The application of superconducting technology in power systems can also improve the stability of the power grid. The superconducting energy storage system can respond quickly when the power grid fails or the demand fluctuates, and provide the necessary power support, so as to ensure the stable operation of the power grid. Due to the properties of zero resistance of superconducting materials, even inefficient clean energy in the past can be used effectively. Because the superconducting technology can reduce the energy loss, it can reduce the operating cost of the power system. Especially in the construction of urban power grid, the use of superconducting cables can improve the efficiency of the power grid.

Chen and others have studied the methods and safety of superconducting technology to other cities, data centers and hospitals [7]. Chen Zhenghua and other scholars analyzed the superconductor model, structure, design, optimization and simulation analysis of superconducting DC cable [8].

3.3. The role of superconducting technology in the traffic

Superconducting maglev trains use the strong magnetic field generated by superconducting materials to allow the trains to hover on the tracks and operate at high speeds. Due to the zero-resistance characteristics of superconducting materials, superconducting maglev trains can operate at faster speeds during operation, with almost no energy loss. At the same time, the stronger magnetic field formed by the superconductors enhances the stability and safety of the train.

Superconducting battery technology uses the characteristics of superconducting materials to achieve ultra-high energy density storage at low temperature, improving the range of electric vehicles and shortening the charging time. In addition, the application of superconducting materials can also improve the motor efficiency of electric vehicles and further reduce energy consumption. Superconducting cable system uses the zero-resistance characteristics of superconducting materials to achieve efficient and low-loss power transmission. This not only improves the efficiency of power transmission, but also saves the volume and weight of the line, saving power consumption for urban traffic systems, such as traffic lights.

Yang Minghao and other scholars have analyzed the electromagnetic coupling of high temperature superconducting electric maglev and the development of high temperature superconductor [9]. Zeng Jingsong and other scholars have carried out dynamic modeling and dynamic response analysis of superconducting maglev vehicles [10].

4. Challenge and optimization outlook

The first is temperature, and their critical temperature remains well below room temperature. This limitation makes the research and application of superconducting technology greatly restricted, because it is necessary to maintain the superconducting state at very low temperature, which makes the research environment of superconducting materials extremely harsh, so the research of superconducting materials will spend a lot of time and money.

Secondly, the preparation process is complex and the cost is high. The preparation of superconducting materials requires high precision equipment and complex process, which makes the cost of superconducting materials high. The cost of raw materials, energy consumption during preparation, and investment in related equipment are all factors leading to high costs.

Then comes the stability and reliability of the material. In practical application, superconducting materials need to have good physical and chemical stability to ensure that the material will not denature and lead to the disappearance of the superconducting state. Therefore, further research on the stability and reliability of superconducting materials is needed to improve the application effect of superconducting technology.

Finally, there are safety problems. There may be some safety problems in the application of superconducting technology, such as magnetic field leakage of superconducting magnet and short circuit of superconducting cable.

This hopes that through these studies, the practical application of superconducting materials can be further removed from people's life. This hopes that other researchers will work on this so that superconducting technology can benefit mankind earlier, even though the path will be difficult.

5. Conclusion

This paper introduces the history of superconductivity, where the phenomenon of superconductivity was discovered in 1911, and the classification of superconductors, low temperature superconductors and high temperature superconductors. This paper also analyzes the application possibilities of superconductors in three fields. In computer science, the application of superconductors can produce high density, low power consumption memory; in energy transmission, superconductors have no

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resistance, current can flow without resistance, improve efficiency, and can support greater current density to transmit more electricity in the same cross-sectional area; in terms of traffic, the magnetic field generated by superconducting materials can hover in orbit and run at high speed. In the end, this paper challenges the development prospect of superconductors. The biggest problem of the difficulty of superconductors is the working temperature, the stability and reliability of superconductors, and finally, the security problem. How to ensure that these problems will not occur is another big problem in the development of superconductors.

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