Applications of Superconductors in Electronic Components and Energy Transmission

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Abstract: Superconductors, due to their zero resistance, enable signal transmission with almost zero energy loss in electronic components, especially excelling in high frequency and high sensitivity. The application of superconducting materials will also enable the miniaturization of electronic components while avoiding the reduced efficiency caused by overheating of electronic components. In terms of energy transmission and storage, the application of superconductors can effectively increase transmission efficiency and avoid energy loss, especially in the field of energy and power. The zero resistance property of superconductors means there no resistance loss during power transmission, which can significantly reduce the power loss caused by resistance in traditional power transmission, improve transmission efficiency, reduce energy waste, and lower power generation costs and carbon emissions. In the field of superconducting energy storage, superconductors can be used to create superconducting energy storage devices that enable rapid storage and release of electricity, effectively regulate the peak-valley difference of the power grid, balance power supply and demand, address the intermittency problem of renewable energy generation, and enhance the stability and reliability of the power grid. Superconducting power generation can also be used to create superconducting generators, which can improve power generation efficiency, power density, reduce equipment size and weight, and lower operating costs.

1 INTRODUCTION

As human civilization moves towards the third energy revolution, energy efficiency and the speed of information transmission have become the key bottlenecks restricting modern development. Compared with traditional conductive materials, the use of superconductors will save energy loss, which is 8% to 15% of the average annual energy loss in power transmission. Since the discovery of high-temperature superconductors in 1986, although more than 100 kinds of high-temperature superconductors have been found so far, only three are useful (Xu, 2023). Some electronic components can be made from this material. Devices made with it have the advantage of high power efficiency and energy conservation, and have obvious economic benefits in terms of energy conservation. The zero resistance and high current-carrying capacity of superconducting materials have drawn much attention to the progress of superconductivity research. Superconducting materials are difficult to apply on a large scale because their performance is greatly affected by temperature and magnetic fields. Combining different superconducting materials, as well as combining superconducting materials with metal materials, can combine the advantages of various conductors. The results of various studies show that the thermal stability, AC loss, mechanical properties, and other properties of the composite superconductor have been improved. In terms of energy storage, unlike using chemical substances to store energy, superconducting magnetic energy storage devices store energy using the magnetic field generated by direct current in superconducting material coils. Once the coil is charged, as long as it remains cool, the energy can be stored indefinitely and hardly decays. This article introduces the development of superconductor materials and their applications in electronic components and energy transmission systems.

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2 MANUFACTURING OF SUPERCONDUCTORS

High-temperature superconductors can be made in the form of sintered ceramics by mixing oxides in their composition with carbonate powder and then heating them in pure oxygen (900 °C -1000 °C) until their resistance disappears. The critical temperature at which they possess the properties of superconductors is 90 K. In terms of chemical composition, the thallium superconductor family is the largest superconductor family, which encompasses almost all the crystal structures that copper-based oxides have. Besides the wide range of crystal structure types, the thallium family is also the most chemically diverse system among the four major families of copper-based oxide superconductors. (Zhang, Sun, & Yu, 2000). Similar to the fabrication of other copper-based oxide superconductors, the synthesis of thallium-based superconductors is accomplished through solid-state chemical reactions at high temperatures, and the raw materials used are generally high-purity TI2O3, BaO2, SrO, and CaO. Fine powders such as CuO were used (Xin, 2003). For copper oxide superconductors at high temperatures (e.g. $YBa_2Cu_3O_7$-δ, YBCO), solid-phase reaction is often employed: high-purity Y_2O_3, $BaCO_3$, and CuO powders are mixed in stoichiometric ratios and then ground multiple times and sintered at high temperatures (900-950 °C) to obtain precursors with good single-phase properties. Subsequent oxygen annealing (400-500 °C) regulates the concentration of oxygen vacancies, significantly affecting the superconducting critical temperature (T_c). To improve flux pinning performance, a nanoscale second phase (such as $BaZrO_3$) can be introduced as an artificial pinning center.

3 APPLICATIONS OF SUPERCONDUCTORS

3.1 Superconductor Transportation

Most iron-based superconductors' parent bodies exhibit metallic behavior with antiferromagnetic order. Superconductivity can be induced by gradually suppressing the antiferromagnetic order of the parent body through means such as applying high voltage. (Li, Tao, & Xu, 2021). Superconducting cables can be classified into low-temperature superconducting and high-temperature superconducting based on the characteristics of superconducting materials. The cooling system in the liquid nitrogen temperature zone is simpler than that in the liquid helium temperature zone, so high-temperature cables have a broader application prospect. (Li, 2017). Superconductor cables can reduce energy loss more than traditional cables and avoid energy loss due to electromagnetic damping. Overall, superconductor cables have the following advantages: low line loss, large current-breaking capacity, small cable volume, etc. At present, countries are also actively developing cold-insulated superconductors. The insulation of this type of cable is mainly distributed in a low-temperature liquid nitrogen environment. Compared with hot-insulated superconductors, it has less loss, higher efficiency, lighter weight, and can transmit power at high density. (Zhu, Bao & Qiu, 2012). For example, the 500 m/77 kV cold-insulated HTS cable developed by Sumitomo Denko of Japan has been demonstrated in the Yokohama power grid with a transmission loss of less than 0.1 W/m·kA; China's "Key Technologies for Superconducting Power Grid" project has enabled 1.2kA / 35kV three-phase AC HTS cables to be connected to the Shenzhen grid, with a multi-layer insulated Dewar tube design, saving more than 20 million kilowatt-hours of electricity per year.

3.2 Application of Superconductors in Electronic Components

At present, large grain superconductors with high critical current density can be prepared by the melting process, which have good application prospects in many engineering fields. A large current flowing through the superconductor generates very little heat, which can reduce the use of liquid helium and develop helium-free magnets when used to make wires. Superconductors can also be widely used in transportation, mechanical processing, and major scientific and technological projects. Superconductor materials are free from liquid helium, for example, used in transformers with lower total loss, lighter weight, and lower cost compared to conventional transformers. It can effectively increase the effective power of the generator. (Liu, 2001). With the development of electricity, FCL (Fault current limator) can also effectively use superconductors, and when the current passing through exceeds its critical current, or the pulse magnetic field exceeds its critical magnetic field, the superconductor changes from the superconducting state to the normal state in a series of operations to limit the current and protect the circuit. Magnetic resonance imaging (MRI) magnets also make effective use of superconductor materials (Wang, Feng, & Zhang, 2000).

Such as the 35kV/1.25kA cable project in Shanghai, which has a transmission capacity of more than five times that of conventional cables with almost no energy loss. Nuclear fusion devices, such as ITER, use Nb_3Sn superconducting magnets to generate 12-13T strong magnetic fields, providing key technical support for plasma confinement. In the medical field, NbTi superconducting coils that operate at 4.2K are core components of medical MRI (1.5-9.4T), while new MgB_2 magnets are driving the development of liquid helium-free MRI systems. In weak electrical applications, SQUID magnetometers have become the gold standard for magnetoencephalography (MEG) and mineral exploration with a sensitivity of 10^{-15}T/ √ Hz. Superconducting qubits, such as Transmon, as core units of quantum computers, have coherent times that exceed 100μs. For transportation, high-temperature superconducting maglev trains (such as the Chengdu test line) and ship propulsion motors (GE 36MW) have shown potential for efficient transportation.

4 CHARACTERIZATION OF SUPERCONDUCTIVITY

Because superconductors have zero resistance and complete diamagnetization properties, hydrogen-rich high-temperature superconductors are usually synthesized under extreme conditions above 100 GPa, and the magnetic signal of the sample is very weak, presenting a huge challenge to the measurement of complete diamagnetization. The characterization of superconductors is mainly based on the phenomenon of zero resistance. After the continuous efforts of scientists to measure and experiment, some measurements have also been made public, such as by the Eremets team. It effectively improved the characterization of hydrogen-rich high-temperature superconductors from zero resistance and complete diamagnetism, flux capture, etc. Chen & Wan (2024) lays a solid technical foundation for superconductors in electronic components and energy transfer. AC impedance spectroscopy can effectively characterize the complex conductivity of superconductors under an alternating electric field, and its imaginary response can reflect the dynamic behavior of flux vortices. Microwave surface resistance measurements (such as the resonant cavity method) are sensitive to the bandgap structure, which has confirmed that copper oxide superconductors have D-wave symmetry characteristics. Recent developments in nonlinear electrical transport measurement techniques, such as high-order harmonic analysis, have provided a new approach to studying superconducting fluctuations and quantum phase transitions. In addition, scanning tunneling microscopy (STM) can directly observe the superconducting energy gap and quasiparticle density at the nanoscale, providing direct evidence for understanding unconventional pairing mechanisms.

5 THE ROLE CHARACTERISTICS OFF ELEMENT IN OXIDE SUPERCONDUCTORS

Since the discovery of superconductors by Bednorz & Muller (1988), element substitution has been A major approach to preparing new materials and manufacturing superconductors, such as cation substitution for obtaining Y series, Bi series, etc. By partially replacing O in high-temperature oxide superconductors with F, and causing changes in the overlapping numbers of other elements in the unit cell, F in F superconductors is less likely to be oxidized and destroyed by external conditions and is much more tolerant than superconductor materials without F. Due to the essential differences between F and O, the substitution of O by F has a series of essential effects on oxide superconductor materials, providing a reference for the exploration of superconducting machines (Deng, Wang, & Chen, 2003).

6 UNCONVENTIONAL SUPERCONDUCTORS

Unconventional superconductors also have properties such as zero resistance, but the formation mechanism of Cup-amber pairs and the symmetry of superconducting wave functions are very different from those of conventional superconductors.

6.1 Heavy Fermionic System

Heavy fermionic systems also weigh electron systems. Heavy fermionic materials have an electron-specific heat coefficient hundreds of times higher than that of ordinary metals at low temperatures. Previously discovered fermionic superconductors were concentrated in 4f or 5f electronic systems. Recently, Luo Xigang et al. conducted experiments to demonstrate the superconducting behavior of heavy fermions in 3d electronic systems. It has been proven that AFe2As2 (A=K, Rb, Cs) do conform to the universal behavior satisfied by heavy fermionic superconductors. (Luo, Wu, & Chen, 2017). Fermions, as one of the earliest discovered classes of unconventional superconductors, have very low superconducting transition temperatures. It may not be of great significance from a practical perspective, but it is significant from a research perspective. Superconductivity has been recognized as one of the most deeply understood phenomena in condensed matter physics. The emergence of heavy fermionic superconductors and the many anomalous properties they exhibit make it a field of study that is both full of contradictions and problems and challenging Dong (2011).

6.2 Copper Oxide Superconductors at High Temperatures

In 1986, Swiss physicist Bednorz and others at IBM LABS discovered copper oxide superconductors with perovskite structures, whose superconducting transition temperature is much higher than the highest known conventional superconductor temperature (Bednorz & Muller, 1986). Copper oxide superconductors are often described as twisted, oxygen-deficient multilayer perovskite structures. Copper oxide superconductors not only have superconductivity at high temperatures, but also a very rich electron phase diagram that varies with load concentration due to an electron correlation effect. (Luo, Wu & Chen, 2017) The crystal structure of copper oxides has quasi-two-dimensional properties and is composed of alternating layers of conductive CuO_2 planes and charge-transport layers (such as CuO chains in YBCO, BiO layers in BSCCO). By chemical doping (such as Sr substitution in $La_{2-x}Sr_xCuO_4$ or oxygen content regulation (such as δ variation in $YBa_2Cu_3O_{7-}δ$, Carriers can be introduced into the insulating parent body to form a superconducting state. Its phase diagram shows a complex competitive order:

1 Antiferromagnetic insulating state: Undoped parent, due to strong Coulomb repulsion (Mott insulation) and antiferromagnetic order. No superconductivity;

2 Underdoped regions: Pseudogap phenomena appear on the left side of the superconducting dome, possibly related to pre-formed electron pairs or topological order;

3 Optimal doping: T peaks at a carrier concentration of 0.16

6.3 Iron-Based Superconductor

In early 2008, Professor Hideo Hosuno's team from Tokyo Institute of Technology in Japan discovered superconductivity at 26K, which immediately drew widespread attention from the superconducting community. Twenty years later, this discovery sparked another wave of research on high-temperature superconductivity. (Kamihar et al. 2008). Since then, scientists have successively discovered a series of iron-based superconductor materials with high transition temperatures. These materials, with FeAs/FeSe layers as their structural core, exhibit layered characteristics similar to cuprates and possible unconventional superconducting mechanisms, but the coexistence of antiferromagnetic order and superconducting states in their parent bodies, multi-orbital electron correlation effects, and higher upper critical magnetic fields offer a new perspective for exploring high-temperature superconducting mechanisms. Iron-based superconductors can be upgraded to above 55 K through element doping (such as Co and Ni replacing Fe), pressure regulation or interface engineering (such as monolayer FeSe/$SrTiO_3$ interface systems), and their rich phase diagrams and electronic structures (such as s± wave pairing symmetry) challenge the conventional BCS theory. (Luo & Chen, 2017). The superconducting properties of on-based superconductors are closely related to their electronic structure. Unlike copper oxides, iron-based superconductors typically present an anti-iron metallic state rather than an insulating state, and their superconductivity can be induced by electron or hole doping. Phase diagram studies suggest that superconducting domes are typically adjacent to antiferromagnetic sequences, suggesting that spin fluctuations may play a significant role in superconducting pairing. Experimental observations of multi-band characteristics and s± wave pairing symmetry support the theory of multi-band superconductivity. Notably, iron-based superconductors exhibit superior performance under strong magnetic fields, such as the upper critical field Hc2(0) of Ba0.6K0.4Fe2As2 reaching over 70T, which gives them a unique advantage in high-field magnet applications. In terms of material preparation, the growth of high-quality single crystals is the key to studying the intrinsic properties. The flux method is suitable for the preparation of "122" type single crystals, while the gas phase transport method is more suitable for "11" type compounds. Thin-film epitaxy techniques, such as MBE, have made a breakthrough in FeSe/STO interface superconductivity research. In application development, the preparation of iron-based superconducting wire strips (such as Ba122) has achieved kilometers-level continuous production, but their critical current density (Jc) still needs to be improved. The main challenges in the current research include the complex interaction mechanisms of multi-band systems, the microscopic origins of interfacial enhanced superconductivity, and the performance optimization of practical materials. In the future, iron-based superconductors are expected to make significant breakthroughs in both fundamental research and practical applications through means such as pressure regulation, interface engineering and nanocomposites.

7 CONCLUSIONS

Superconductors, as a new type of material with advantages such as zero resistance, can be widely used in various future electronic products, have attracted academic attention so far. For example, superconducting motors, superconducting cables, maglev trains, etc. If people can effectively utilize the advantages of superconductors such as complete demagnetization, magnetic fields can be used to effectively transform various electronic products.

Conclusion: Conventional superconductors (such as NbTi, Nb_3Sn): following the BCS theory, phonon-mediated S-wave pairing, critical temperature usually < 30 K, with complete diamagnetization and zero resistance properties. It is the most widely used type of superconductor. The core application areas of superconductors are energy transmission and electronic devices. Superconducting cables (such as MgB_2 cables) can carry five times the current density of traditional cables, but require a low-temperature system to maintain. A fault current limiter (FCL) enhances grid stability. Superconducting quantum interferometers (SQUIDs) are used for detecting extremely weak magnetic fields (medical, geological). Applications of superconducting single-photon detectors (SNSPDS) in quantum communications. Superconducting cables (such as MgB_2, YBCO) can transmit current without resistance loss, significantly improving grid efficiency (the transmission loss of about 5-10% in traditional grids can be reduced to nearly 0%). It is suitable for urban power supply and renewable energy grid connection (such as long-distance transmission of wind power and photovoltaic power). Superconducting magnetic energy storage (SMES) can charge and discharge instantaneously for grid frequency regulation and emergency power supply. Superconducting fault current limiter (FCL) prevents grid short-circuit accidents. Research on superconductors aims to explore the physical mechanisms of zero resistance and complete diamagnetism (the Meissner effect) and to develop their revolutionary applications in energy, healthcare, transportation and other fields. The discovery of high-temperature superconducting materials has greatly boosted strong electrical applications such as superconducting cables and maglev trains, as well as weak electrical applications such as quantum computing and superconducting detectors. The current research is focused on raising the critical temperature of superconductivity, understanding the mechanism of unconventional superconductivity, and addressing the bottlenecks in the large-scale production of materials. Future breakthroughs could achieve room-temperature superconductivity, revolutionize power transmission and storage technologies, and provide new solutions for clean energy and efficient electronic devices.

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