From Alloys to Non-Metals: The Evolution of Superconducting Materials

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Abstract. Superconducting materials, which exhibit distinctive properties such as zero electrical resistance, perfect diamagnetism, and quantum tunneling effects, are of great practical significance and possess immense potential for application development. In the fields of power transmission, medicine, transportation, quantum computing, industry, and national defense, superconducting materials are becoming increasingly important. In recent years, with the progressive maturation of fabrication techniques, high-temperature superconducting materials have transitioned from experimental research to practical applications. Meanwhile, relentless investigation into the mechanisms of superconductivity has led to the emergence of novel superconducting materials. To further elucidate the landscape of superconductivity, this article first reviews the historical development of superconductors, their physical properties, and the classification of superconducting materials. It then introduces representative alloy-based, metal oxide, and emerging non-metallic superconducting materials. This study systematically examines the fundamental structures, performance characteristics, fabrication techniques, and current application progress for each category of superconducting material. Finally, it offers an outlook on future directions for enhancing the performance and expanding the practical applications of high-temperature superconducting materials.

Keywords: superconducting materials, superconducting application, superconducting mechanism.

1 Introduction

Superconducting is a phenomenon that special materials exhibiting two core properties, which are zero electrical resistance and perfect diamagnetism, below a specific critical temperature (Tc). The zero electrical resistance, indicated the DC resistance of a superconductor suddenly vanishes, when the temperature drops below the critical temperature, allowing current to flow continuously through the material without attenuation. For example, the mercury (Hg) exhibits zero resistance at 4.2K, enabling perpetual current flow without energy loss, which is the key property for power transportation. The perfect diamagnetism let superconductors completely

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expel external magnetic field lines in a magnetic field, resulting in zero internal magnetic field inside. This property forms the physical foundation of magnetic levitation technology, enabling future maglev trains to spontaneously float above tracks without requiring continuous power to sustain the magnetic field.

Since the first superconductor was discovered in 1911 [1,2], various applications of superconductors have been investigated. In 1962, British physicist Josephson proposed a theoretical prediction: when an extremely thin insulator is sandwiched between two superconductors, electron pairs can tunnel through the insulating barrier to form a superconducting tunneling current [3]. Within less than a year, this prediction was experimentally verified. This unique physical phenomenon, known as the Josephson effect (also termed the quantum tunneling effect), forms the foundation for applications in quantum detection and quantum computing, pioneering the field of electron dynamics. It provided evidence for Cooper pair motion in superconductors and deepened our understanding of the nature of superconductivity. Today, superconductivity represents one of the most iconic quantum phenomena in condensed matter physics and constitutes a strategic-level technology driving transformative advancements across power transmission, medicine, transportation, quantum computing, industry, national defense, and other fields [4].

Since the accidental discovery of superconductivity, scientists have sought to uncover its fundamental mechanisms and develop high-temperature superconducting technologies to enhance practical applications. Beginning in the 1920s, numerous researchers dedicated themselves to this pursuit. Despite years of exploration yielding no substantial breakthroughs, high-temperature superconductivity research reached an impasse by the late 1960s; some even concluded that superconductivity could only occur at extremely low temperatures. This changed in 1986, when new metal oxides raised Tc to 33 K, ushering in a new era for high-temperature superconducting applications [2]. The development of superconducting materials has evolved from simple metals to alloys, metal oxides, and then to complex compounds, with their critical temperatures increasing significantly. Several materials have already entered real-world applications. Among alloys, leading candidates include NbTi and Nb3Sn for low-temperature applications, and MgB2 for higher-temperature operation. Within metal oxide systems, copper-based and iron-based oxides show great potential [5].

Following the discovery of superconductivity, physicists have continually sought to understand its fundamental nature and have proposed phenomenological theories to explain it. However, these early theories failed to fully account for the underlying cause of superconductivity. The debate persisted until 1957, when the Bardeen-Cooper-Schrieffer (BCS) theory was proposed. This theory describes superconductivity as a macroscopic quantum effect: electrons with opposite spins and momenta in a metal can pair to form Cooper pairs, which move through the crystal lattice without dissipation, generating superconducting currents. The BCS theory successfully explains numerous phenomena in conventional superconductors and remains the most successful microscopic theory of superconductivity to date [2]. However, as new classes of superconductors were discovered—including metal oxides, organic superconductors, and magic-angle graphene, the BCS framework required refinement or extension. Therefore, it is necessary to review various superconducting materials systematically, comparing their properties and evaluating candidate explanations for their superconducting behavior.

This essay introduces three case studies on recent research progress in different superconducting materials and compares the advantages and limitations of each through data analysis. Furthermore, the author proposes suggestions to address these limitations. This article is organized into four sections: 1. Introduction, which outlines the general research progress of superconductors; 2. Case Studies and Analysis, which presents three categories of superconductors, analyzing their respective advantages and disadvantages alongside detailed experimental procedures and synthesis methods; 3. Summary and Suggestions, which discusses the strengths and weaknesses of each superconducting design and offers the author's perspectives; and 4. Conclusion, which summarizes the findings of each investigation.

2 Case and analysis

2.1 Alloy superconductor

Alloy superconductors are superconducting materials formed by alloying two or more metallic elements, with their superconducting mechanism primarily based on electron-phonon interactions (traditional BCS theory). Typical examples include niobium-titanium alloys (Nb-Ti, $T_c \approx 9.5K$) and niobium-zirconium alloys (Nb-Zr, $T_c \approx 10.8K$). Through multi-component alloying (e.g., adding tantalum to form Nb-Ti-Ta), these materials can significantly enhance critical magnetic field (H_{c2} exceeding 15 T) and critical current density (Jc), making them core materials for high-magnetic-field applications. The advantages of alloy superconductors lie in their superior mechanical properties (enabling fabrication into multi-core wires), high stability (suppressing flux pinning through copper-based composite conductors), and lower cost compared to oxide superconductors. Currently, niobium-titanium alloys dominate 95% of the low-temperature superconducting market, finding extensive use in magnetic resonance imaging (MRI), particle accelerators, and magnetic systems for nuclear fusion devices. [6,7]

The fabrication of Alloy superconductor mainly come from a binary diffusion. Here the fabrication of Nb_3Sn was presented. As shown in Fig. 1. Basically, the fabrication of Nb_3Sn including directly diffusion and bronze method. And the bronze method by adding Cu into Nb-Sn system, provide advantages and stable fabrication process. The core function of adding copper to Nb_3Sn superconductors lies in achieving stable tin supply and performance optimization through the bronze method process. The high plasticity of Cu mitigates the risk of brittle fracture in Nb_3Sn. Simultaneously, it dissolves Sn elements through solid solution to form a Cu-Sn alloy. During subsequent heat treatment, tin atoms diffuse into the niobium core to generate the Nb3Sn superconducting phase. Meanwhile, Cu addition lowers the reaction temperature to 650-750 °C, preventing grain coarsening caused by high temperatures. Furthermore, the Cu matrix encapsulates the multi-core structure through plastic deformation, significantly enhancing the mechanical strength [6].

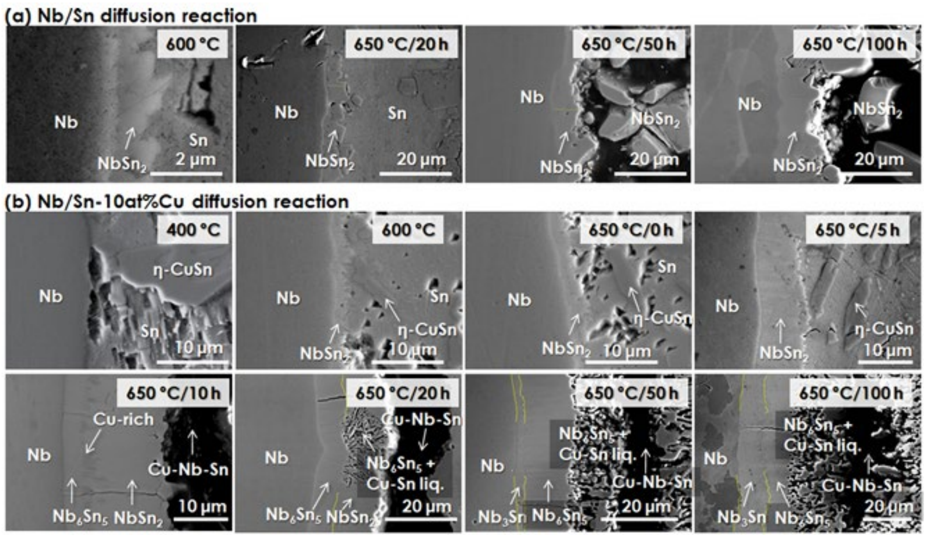

Fig. 1. SEM image of Nb3Sn fabrication based on (a) Nb-Sn direct diffusion (2) bronze method for Nb/Sn-10at%Cu diffusion reaction [6].

The core challenges of Nb_3Sn superconductors lie in material brittleness and complex fabrication processes. The cubic crystal structure results in inherent high brittleness, making direct shaping via conventional metalworking methods. Though the bronze method introduced Cu as 3rd phase and largely ease the inner brittleness, the complex of the process is limited for various parameter such as Sn content and heat treatment temperature, requiring precise control to prevent non-superconducting phases like Nb_6Sn_5. High costs, coupled with constraints from raw materials (high-purity Nb and Sn) and equipment investments, limit large-scale production of alloy superconducting materials.

2.2 Metal oxides superconductor

The metal oxides superconductor is discovered at 1986, and was the first superconductor group to overcome the 77K, which the temperature could be fabricated by liquid nitrogen. The high temperature Tc largely reduce the application cost for superconductor. The typical metal oxides supercpnductor is Bismuth-based superconductors, primarily comprising copper oxide systems such as $Bi_2Sr_2CuO_8$ (Bi-2201), $Bi_3Sr_3CaCu_3O_8$ (Bi-2212), and $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223). These materials exhibit layered perovskite structural variants, with superconducting layers composed of CuO_2 planes separated by Bi_2O_3 and alkaline earth metal layers, resulting in pronounced anisotropic properties. Among those materials, The Tc of Bi-2223 achieving the highest value of 110 K. It was regarded as the first high-temperature superconductor realized industry application.

The fabrication of metal oxides superconductor mostly come from powder-in-tube (PIT) method [8]. For example, Bi-2212 & Bi-2223 powders were firstly synthesized by solid diffusion or liquid chemical reduction. Then, the powder was sealed into Ag tubes or Ag-Mg alloy tubes, then draw them multiple times to form multi-core composite wires. By controlling the processing rate (10%-20%) for each time, the density of the superconductor core is enhanced, and the final bendable wire could be achieved.

The limitation of metal oxides superconductor located for its pronounced anisotropy properties and critical current density (Jc) exhibits steep decay under perpendicular magnetic fields. The former defect restricted current flow to the CuO_2 plane orientation, which limits the effective current-carrying in cross direction, significantly deteriorated its practical application efficiency. The later defect failing to meet the requirements of large-scale high magnetic field environment. For example, Bi-2223 achieves only 7 T irreversible field at liquid nitrogen temperatures, far below to the 15 T which should be reach for fusion magnet parts or high-energy accelerators.

2.3 Non-metal superconducting material, Magic angle graphene

Until 2018, all superconductor discovered is metal-based alloy or compounds. At least needs metal element for doping. However, the appearance of magic angle graphene opened a new world for the recognition of superconductor. When overlay 2 single layer graphene into particular angle (magic angle, 1.1°), the layered graphene could show superconductivity at low temperature. The first superconductor based on magic angle graphene is shown in Fig. 2 [9].

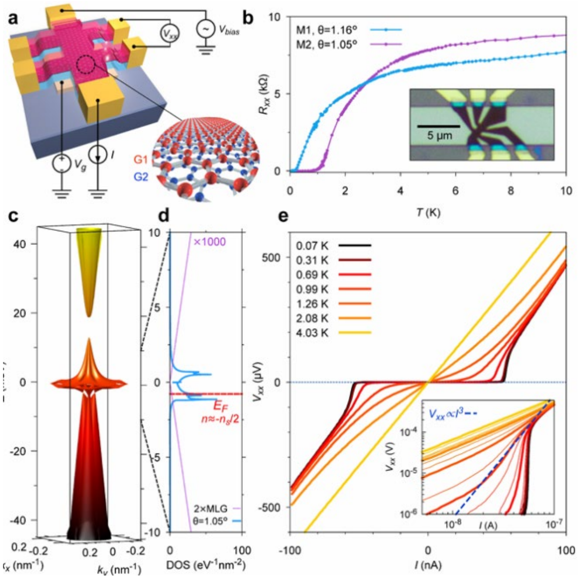

Fig. 2. First device base on magic angle graphene and its superconductivity in a graphene superlattice [9].

The further investigation of the material unveiled a new mechanism for superconducting phenomenon. Though the mechanism is not very clear so that, a possible explanation is list as below: Rotate two layers of graphene at the magic angle alters the Dirac cone band hybridization effect in the bilayer graphene, opening an energy gap in the originally perfect Dirac cone and renormalizing the Fermi velocity at the Dirac point. This band hybridization shares common ground with orbital hybridization: Each carbon atom in graphene possesses four valence electrons. Three of these form sp^2 hybridized orbitals to bond with three neighboring carbon atoms, while the remaining electron resides in a p orbital perpendicular to the graphene plane.

When the two layers are rotated, a remarkable hybridization occurs between their electronic orbitals. This orbital hybridization induces energy band hybridization, which can be visualized as band hybridization. The effect of this band hybridization is that the energy band structure, originally conical (related to the Dirac equation), changes as the rotation angle varies [9]. However, when adding more layer and twist, the superconductivity of the system becomes unpredictable, adding more mystery to the magic graphene superconductor [10].

The core challenges of magic angle graphene superconductors are in three dimensions: the unclear superconducting mechanism, bottlenecks in preparation techniques, and stringent experimental conditions. Although it is confirmed that isotope substitution experiments that electron-phonon coupling plays a crucial role in superconductivity, competing theories (such as spin fluctuations and inter-valley coherence) persist regarding the pairing mechanism, lacking a unified explanation. At the fabrication level, existing mechanical exfoliation methods struggle to precisely control the 1.1° magic angle with yields below 10%. in addition, the superconducting state remains stable only below 1.7 K. The critical current density (Jc) is constrained by two-dimensional planar anisotropy, failing to meet the requirements for high-field magnet applications.

3 Summary

The advantages and disadvantages of the 3 types superconducting materials are listed in Table. 1. Firstly, alloy superconductors, such as NbTi and Nb Sn, constitute the predominant class in low-temperature applications owing to their exceptional mechanical robustness and cost-effective fabrication. Their high ductility enables precise shaping into wires and cables, rendering them indispensable in magnetic resonance imaging (MRI) systems and high-energy accelerators. These materials exhibit stable performance under cryogenic conditions and maintain reliable critical current densities in high magnetic fields. However, their utility is constrained by narrow processing windows, necessitating tight control over alloy composition and thermal treatments to preserve superconductivity. Additionally, their reliance on liquid helium cooling (4.2 K) limits scalability. Furthermore, these alloys face challenges when competing with emerging materials for energy-efficient, high-temperature applications.

Metal oxide superconductors dominate the high-temperature superconductor landscape, encompassing Bi-based, Cu-based, and Fe-based systems. These materials exhibit superconductivity above the liquid nitrogen temperature (77 K), substantially reducing operational costs and enabling large-scale manufacturing. Despite these advances, intrinsic anisotropy complicates current distribution in magnetic fields, leading to performance degradation under extremely strong magnetic conditions. Furthermore, their brittle nature and sensitivity to mechanical stress impede structural integration. While high-temperature superconducting materials offer economic advantages, persistent challenges in long-length fabrication and cost reduction continue to limit their widespread deployment in the energy and transportation sectors.

Magic-angle graphene, realized through twisted bilayer graphene, represents a paradigm shift in superconductivity research, giving rise to non-metallic carbon-based structures and novel electronic correlation effects. Its distinctive superconducting states have spurred intense interest in deepening the fundamental understanding of superconductivity. Theoretical models suggest unconventional pairing mechanisms, such as spin-fluctuation-mediated superconductivity, which could redefine condensed matter physics. However, experimental challenges remain formidable: achieving precise twist angles (<0.1° in some cases, typically ~1.1°) with high uniformity remains elusive, and large-scale synthesis via chemical vapor deposition (CVD) suffers from low efficiency. Moreover, the superconducting phase is fragile, requiring ultra-high vacuum and cryogenic conditions for stability. While promising for next-generation quantum devices, these technical barriers and the absence of a unified theoretical framework hinder its industrial adoption.

Table 1. Advantages and disadvantages of the various superconducting materials.

Type	Advantages	Disadvantages
Alloy superconductor	-Superior mechanical properties -Low cost fabrication -High stability	-Narrow window for production -Low Tc
Metal oxides superconductor	-High Tc -Mature fabrication process	-pronounced anisotropy -decay under magnetic fields
Magic angle graphene	-Non-metal related -Novel superconducting mechanism	-unclear mechanism, -bottlenecks in preparation -stringent experimental conditions

4 Conclusion

Superconducting materials exhibit zero electrical resistance, perfect diamagnetism, and quantum tunneling effects, offering considerable scientific significance and broad application potential across power transmission, medical imaging, transportation, quantum computing, industrial manufacturing, and national defense. In recent years, advances in material synthesis have enabled high-temperature superconductors to transition progressively from laboratory research to practical deployment. Meanwhile, deepening insights into superconducting mechanisms continue to drive the discovery of novel superconducting compounds. This review systematically examines the historical development, fundamental properties, and classification framework of superconducting materials. It focuses on the structural characteristics, performance-tuning mechanisms, fabrication advances, and current application scenarios of representative alloy superconductors, metal-oxide superconductors, and emerging non-metallic superconductors. Finally, it outlines prospective strategies for enhancing the performance of high-temperature superconductors and broadening their technological impact.

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