

An Engineering Perspective on the Progress and Implementation of Superconducting Materials: Insights from Low- and High-Temperature Superconductors and Application

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ABSTRACT

Superconductivity is a fascinating phenomenon where certain materials exhibit zero electrical resistance and expel magnetic fields through diamagnetism when cooled below a specific critical temperature (T_c). This unique behavior, characterized by the Meissner effect, has the potential to transform various industries, including energy, healthcare, transportation, and communications. This comprehensive analysis explores both low-temperature superconductors (LTS) and high-temperature superconductors (HTS), highlighting their distinct properties, significant applications, and the challenges associated with their implementation. LTS materials, such as NbTi and Nb₃Sn, are essential for high-field applications like MRI machines and particle accelerators, but they require costly liquid helium for cooling. On the other hand, HTS materials like YBCO and BSCCO can be cooled with liquid nitrogen, making them more affordable and expanding their applications in power transmission, magnetic levitation systems, and advanced electronics. Recent research is also focused on achieving room-temperature superconductivity and increasing critical temperatures, which could make superconducting materials more accessible and efficient, potentially revolutionizing key technologies and infrastructure. This overview summarizes the current state of research and outlines future directions, emphasizing the need for a multidisciplinary approach to fully realize the potential of superconducting materials.

Keywords: Superconducting materials; high-temperature superconductors; low-temperature superconductors; room-temperature superconductivity; cryogenic cooling

INTRODUCTION

Superconductivity originated in the early 20th century, driven by an increasing interest in the behavior of materials at cryogenic temperatures. In 1908, Heike Kamerlingh Onnes, a physicist from the Netherlands affiliated with Leiden University, achieved the liquefaction of helium, achieving temperatures below 4.2 Kelvin. This significant advancement permitted scientists to investigate the electrical characteristics of metals in proximity to absolute zero.

In 1911, Kamerlingh Onnes made a groundbreaking discovery: upon cooling a sample of mercury to 4.2 K, its electrical resistance suddenly reduced to zero. He coined this occurrence “superconductivity,” marking the first identification of a novel state of matter. For this pioneering research, he was honored with the Nobel Prize in Physics

in 1913. Throughout the 1910s and 1920s, additional elemental superconductors such as lead and tin were identified; however, the fundamental physics governing these materials remained obscure. During this period, researchers also noted an intriguing phenomenon: superconductors exhibit the expulsion of magnetic fields. This effect, subsequently referred to as the Meissner effect, was experimentally validated in 1933 by Walther Meissner and Robert Ochsenfeld, confirming that superconductivity constitutes not merely flawless conductivity but a separate thermodynamic phase.

The theoretical framework surrounding superconductivity began to take shape in the mid-20th century. In 1935, Fritz London and Heinz London proposed a series of equations—now known as the London equations—to articulate the electromagnetic behavior of superconductors, particularly concerning the Meissner

effect. Although these equations successfully described certain phenomena, they were phenomenological and did not elucidate the underlying microscopic mechanisms. In 1950, Vitaly Ginzburg and Lev Landau presented the Ginzburg–Landau theory, integrating quantum field theory with thermodynamics to characterize the superconducting order parameter, thereby establishing a groundwork for comprehending superconducting vortices and the distinctions between type I and type II superconductors.

A significant advancement occurred in 1957, when John Bardeen, Leon Cooper, and Robert Schrieffer unveiled the BCS theory, which continues to be the predominant microscopic explanation for superconductivity. According to BCS theory, electrons within a superconductor form Cooper pair, facilitated by lattice vibrations (phonons), enabling their movement without resistance. The theory adeptly accounted for various experimental observations and forecasted energy gaps, isotope effects, and specific heat behaviours. For this seminal contribution, the authors were awarded the Nobel Prize in Physics in 1972.

The latter half of the 20th century witnessed a surge in practical applications alongside the advancement of low-temperature superconductors (LTS). Materials such as niobium-titanium (NbTi) and niobium-tin (Nb_3Sn) became integral in superconducting magnets for MRI apparatus, particle accelerators such as CERN's Large Hadron Collider, and experimental fusion reactors. NbTi, recognized as a superconductor in the 1960s, remains the most prevalently utilized commercial superconductor due to its ductility and elevated critical current capacity.

Superconducting materials have numerous potential uses across diverse industries, ranging from high-efficiency power generation to sophisticated magnet applications. The increased industry involvement in HTS research and development projects in rapidly developing countries has driven substantial progress in these fields (K. Sato 2008a; University at Buffalo 2024a, 2024b; K. Wang et al. 2022). In the electric power domain, superconductors facilitate the development of high-efficiency power devices, enhancing power generation and transmission while reducing energy loss (Blaugher 1996; Nexans 2024; Nikkei staff writers 2022; NREL 1996; Oestergaard et al. 2001). These materials promise transformative advancements in electric power and high-field magnet technology, enabling high-efficiency electric power generation (Santos et al. 2023; Yao & Ma 2021), high-capacity loss-less power transmission (Barnes et al. n.d.), and compact, lightweight electrical equipment (Clynes 2023; Senatore & Rivkin 2019; Toshiba Energy Systems & Solutions Corporation 2022). Superconductors are also essential in advanced magnet applications, including magnetic resonance imaging (MRI) systems and particle accelerators, which

necessitate ultra-strong magnetic fields (Bernstein & Noudem 2020; R. G. Sharma 2021c; Yao & Ma 2021). Furthermore, high-speed maglev transportation (Marchio 2024; SCMAGLEV n.d.), nuclear magnetic resonance (NMR) systems (CCAS 2024; F. Smith & P. Slichter 2006), next-generation high-energy particle accelerators (Sundahl et al. 2021a; Valente-Feliciano et al. 2022; Yao & Ma 2021), and nuclear fusion reactors (Haaack 2024; Temple 2022; Whyte et al. 2016) stand to gain significantly from the application of superconducting materials. In addition to these applications, superconductors enhance the performance of sensors, detectors, and a range of other electronic components (Braginski 2019; Seidel 2015a).

Figure 1 illustrates how critical temperatures have evolved from the first superconductivity in mercury found in 1911 to the present, so stressing scientific successes including the late 20th-century discovery of high-temperature superconductors (HTS) (Ray 2016). Figure 1 shows that the early 20th-century discovered first superconductors, notably mercury (Hg) and lead (Pb), had critical temperatures much below 10 K. These materials limited their useful purposes since they needed to be extremely cooled by liquid helium. Midway through the 20th century, materials like niobium-titanium (NbTi) and Nb_3Sn which raised the critical temperature to roughly 18 K made notable progress.

Although the practical applications of superconductors were increased by the discovery of materials with increasingly higher critical temperatures, the theoretical underpinnings of superconductivity were laid in 1957 with the creation of the Bardeen-Cooper-Schrieffer (BCS) hypothesis (J. Bardeen et al. 1957b, 1957a; Q. Chen et al. 2024). This hypothesis provided the first microscopic explanation of superconductivity and shed light on the mechanics underlying materials' zero electrical resistance at low temperatures especially in typical, low-temperature superconductors.

The emergence of electrode superconductors, where excess electrons function as anions under high pressure, alongside computationally designed materials with customized electronic attributes, signifies a pivotal advancement; additionally, high-entropy alloys and multi-phase materials synthesized under extreme conditions have exhibited dual-phase superconductivity, as demonstrated in a TaNbZrHfTi alloy, while research confirms that bcc-structured HEAs sustain high critical current densities under significant pressure, essential for practical applications, and novel superconducting behaviours in doped layered materials have been unveiled through high-pressure methods) in Nd-doped compounds and in praseodymium-doped $\text{FeSe}_{0.5}\text{Te}_{0.5}$, where high pressure enhances critical current densities without affecting transition temperatures.

2016; Guo et al. 2018; Patel et al. 2019). These domains are essential for generating high-resolution photographs of soft tissues in the human body. The efficacy and consistency of the magnetic field, necessary for precise imaging, rely on NbTi's capacity to transmit substantial currents without resistance (Berlincourt 2016; Patel et al. 2019; W. Sun et al. 2023). An MRI machine typically employs superconducting coils composed of NbTi, which are cooled to 4.2 K with the aid of liquid helium. The magnetic fields produced by these magnets range from 1.5 to 3 Tesla, adequate for generating the detailed imaging necessary for medical diagnostics (Baig et al. 2014; Thekkethil et al. 2023).

Protons are steered and accelerated to near-light speeds in particle accelerators such as the Large Hadron Collider (LHC) at CERN using NbTi superconducting magnets (Berlincourt 2016). Usually about 1.9 K, the superconducting magnets must run in very low temperatures to preserve their superconducting condition, attained by superfluid helium cooling. These magnets produce magnetic fields of more than 10 T, which allows exact particle beam control (Krishna 2023). The 27-kilometer-round tunnel at the LHC is guided by strong magnetic fields produced by NbTi superconducting magnets (CERN 2024b). The magnets must function without dissipating energy for effective particle acceleration in high-energy physics experiments.

NIOBIUM-TIN (Nb₃Sn)

Nb₃Sn exhibits greater brittleness compared to NbTi; however, it provides a superior critical temperature (T_c) of 18.1 K and a critical magnetic field in the range of 20-25 T (CERN 2024b; W. Sun et al. 2021, 2023). This renders it particularly advantageous in applications necessitating more robust magnetic fields than those offered by NbTi. Nb₃Sn is utilized in situations where magnetic fields surpass the performance of NbTi (De Frutos et al. 2017; Dietderich & Godeke 2008; W. Sun et al. 2023). The elevated critical temperature and magnetic field facilitate the development of more powerful and efficient magnets. Nonetheless, Nb₃Sn exhibits mechanical brittleness, presenting challenges in handling it relative to NbTi (W. Sun et al. 2021, 2023). To address this challenge, Nb₃Sn is generally produced using a "react-and-wind" technique, in which the material is shaped into the intended magnet configuration before undergoing a heat treatment that facilitates the formation of the superconducting phase (Nishijima et al. 2008; Puigsegur 2004; Sundahl et al. 2021a). The enhanced magnetic field strength provided by Nb₃Sn is essential for future technologies, including nuclear fusion reactors. In ITER, a worldwide nuclear fusion research and engineering

initiative, Nb₃Sn superconducting magnets are employed to confine the plasma essential for attaining nuclear fusion (Haack 2024; Neil Mitchell 2011). These magnets must produce exceptionally powerful fields, exceeding 13 T, to regulate and stabilize the high-temperature plasma (Bajas et al. 2012; N Mitchell et al. 2020; Mondonico et al. 2010; X. Xu 2017). In the ITER fusion reactor, substantial superconducting magnets composed of Nb₃Sn are crucial for confining plasma that attains temperatures in the millions of degrees (Haack 2024; Shikov et al. 2004; X. Xu 2017). These magnets function at low temperatures, approximately 4.5 K and their capacity to produce intense magnetic fields is essential for attaining the conditions required for nuclear fusion (Dolan & Ivanov 2013; R. G. Sharma 2021b).

Advanced MRI systems and nuclear magnetic resonance (NMR) devices also feature Nb₃Sn since stronger magnetic fields improve imaging sensitivity and resolution (Barzi & Zlobin 2019; W. Sun et al. 2023; X. Xu 2017). Particularly in specialist research environments, these systems gain from Nb₃Sn's capacity to endure stronger fields than NbTi. High-field NMR instruments utilized in molecular research employ Nb₃Sn to produce magnetic fields exceeding 20 T, allowing researchers to examine molecule structures with unparalleled precision (Barzi & Zlobin 2019; W. Sun et al. 2021). These powerful magnetic fields provide a more detailed examination of intricate biological components, including proteins and DNA (Wei et al. 2022)(Markwick et al. 2008; Pintér et al. 2021).

BULK IRON-BASED SUPERCONDUCTORS (BULK FE-SE)

With a critical temperature (T_c) of about 8 K, iron selenide (FeSe) in bulk form is categorized as a low-temperature superconductor (LTS). This gives bulk FeSe similar low-temperature superconducting characteristics to other LTS materials such as NbTi and Nb₃Sn (Dong et al. 2020; Jiao et al. 2024; Y. Li et al. 2024; Ying et al. 2018; Zhou et al. 2019). FeSe's possibility for significant T_c increase under appropriate conditions, like doping and pressure application, however, makes it especially fascinating (Jiao et al. 2024; J. P. Sun et al. 2017; R. Zhang et al. 2020; Shiqing Zhang et al. 2023). Although bulk FeSe is still an LTS material, its adaptability and capacity to show superconductivity at higher temperatures in modified forms continue to be the focus of active superconductivity research (Y. Li et al. 2024; Nagata et al. 2024; Ying et al. 2018) While bulk FeSe is categorized as an LTS, its superconducting characteristics can be greatly improved under specific conditions—discussed later in the HTS section—where thin-film and doped FeSe show greater T_c values, reaching up to 80 K.

MAGNESIUM DIBORIDE (MgB₂)

Discovered in 2001 and with unusual characteristics, magnesium diboride (MgB₂) is a remarkable low-temperature superconductor (LTS) that has drawn a lot of research subsequently (Buzea & Yamashita 2001; Krinitsina et al. 2021; Putti & Grasso 2011; Yamamoto 2022). MgB₂ has the highest T_c of all standard LTS materials with a T_c of roughly 39 K (Acharya et al. 2016; Uchida 2015). This rather high critical temperature distinguishes MgB₂ from conventional LTS materials such as niobium-titanium (NbTi) and niobium-tin (Nb₃Sn) since it lets the use of liquid hydrogen or cryocoolers for cooling rather than the more costly liquid helium (Krinitsina et al. 2021)(Patel et al. 2017). For some superconducting uses, MgB₂ is also chemically simple and plentiful, which makes it a more reasonably priced component (Buzea & Yamashita 2001; Krinitsina et al. 2021; Putti & Grasso 2011). MgB₂ possesses a straightforward crystal structure and a comparatively high critical temperature for a low-temperature superconductor, facilitating superconducting properties at elevated temperatures relative to conventional low-temperature superconducting materials (Bouquet et al. 2002)(Rogado et al. 2002). MgB₂ exhibits a critical magnetic field of approximately 20 T, which, while lower than that of Nb₃Sn, remains adequate for numerous practical applications (Buzea & Yamashita 2001; Caplin et al. 2003; Dou et al. 2006; Gozzelino et al. 2011; Noguchi et al. 2009). MgB₂ demonstrates superior performance in high-frequency applications attributed to its low surface resistance at microwave frequencies, rendering it appropriate for devices like resonators and filters (Hein 2002; Jin et al. 2007; Lee et al. 2019).

NbTi remains the predominant material utilized in MRI machines; however, MgB₂ is under investigation as a viable alternative owing to its elevated critical temperature and lower cooling expenses (Iwasa 2017; Majoros et al. 2022; Weijun Yao et al. 2010). The utilization of cost-effective cryogens, such as liquid hydrogen or mechanical cryocoolers, positions MgB₂ as a promising candidate for next-generation MRI systems, especially in areas where helium availability is restricted or expensive (Patel et al. 2017; Stautner et al. 2014). Because of its higher operating temperature, MgB₂ is also being considered for application in superconducting power lines, where it could improve energy transmission efficiency while decreasing cooling costs (Krinitsina et al. 2021; Marian et al. 2018; Yamamoto 2022). These cables are ideal for power grids and other energy applications that necessitate the lossless transfer of electricity over long distances due to their ability to deliver high currents with minimum losses (Grilli et al. 2014; Marian et al. 2018; Putti & Grasso 2011).

MgB₂ is employed in applications necessitating robust yet not extreme magnetic fields, such as nuclear magnetic resonance (NMR) equipment and smaller scientific research facilities (Krinitsina et al. 2021; J. Li et al. 2020; Yamamoto 2022). MgB₂ superconducting wires are increasingly utilized in these applications owing to their advantageous cost-to-performance ratio relative to other low-temperature superconductors (Buzea & Yamashita 2001; Prikhna et al. 2024; Putti & Grasso 2011). The potential use of MgB₂ in maglev transit systems is also being investigated (Krinitsina et al. 2021; Noudem et al. 2020). Despite the prevalence of HTS materials in high-speed magnetic levitation, MgB₂ could be a viable option for creating affordable maglev systems in some settings because of its lower cost and greater T_c (Buzea & Yamashita 2001; Putti & Grasso 2011; Shadab et al. 2024). Although MgB₂ presents numerous benefits compared to conventional low-temperature superconductors, such as an elevated critical temperature and diminished cooling expenses, it encounters certain obstacles. The brittleness of MgB₂ complicates its fabrication into long wires; however, developments in production techniques, such as powder-in-tube (PIT) technologies, are mitigating these challenges (Buzea & Yamashita 2001; Prikhna et al. 2024; Putti & Grasso 2011). Furthermore, MgB₂ possesses lower critical magnetic fields compared to Nb₃Sn, constraining its applicability in ultra-high-field scenarios. Nonetheless, its cost-effectiveness and superior superconducting characteristics provide MgB₂ an attractive candidate for numerous superconducting applications (Krinitsina et al. 2021; Prikhna et al. 2024; Tolendiuly et al. 2024; Yamamoto 2022).

THE ROLE OF CRYOGENIC COOLING

The superconducting materials NbTi and Nb₃Sn possess critical temperatures (T_c) significantly lower than the boiling point of liquid helium at 4.2 K. To preserve their superconducting state, these materials must be maintained below their respective critical temperatures: 9.3 K for NbTi and 18.1 K for Nb₃Sn (W. Sun et al. 2021; P. Zhang et al. 2019). This necessitates exact and ongoing cryogenic cooling. Liquid helium is the optimal coolant owing to its extremely low boiling point, yet it presents certain complications (Lavrenchenko & Kravchenko 2020; Lebrun 2007; S.W. Van Sciver n.d.). Helium is costly due to its scarcity, and its management and storage necessitate sophisticated cryogenic apparatus. Maintaining such low temperatures in large-scale applications increases the complexity and costs associated with the infrastructure. The utilization of NbTi and Nb₃Sn is frequently confined

to advanced sectors, such as particle accelerators and medical imaging (MRI), where the criticality of the applications warrants the associated costs.

Apart from the expenses, liquid helium offers operating difficulties (Pezzetti 2021; Steven W. Van Sciver 2012; Weisend II 2021). It evaporates fast and needs frequent replacement, which increases costs even more and complicates transportation. Systems running liquid helium must thus be painstakingly built to reduce helium loss and guarantee effective cooling. These limitations indicate that although NbTi and Nb₃Sn have remarkable superconducting performance, their practical application is generally limited to settings where the advantages exceed the major cooling expenses (W. Sun et al. 2023). Notwithstanding these constraints, the unmatched characteristics of superconducting magnets—such as low electrical resistance and the capacity to create strong magnetic fields—make liquid helium cooling an essential feature of contemporary superconducting technology.

YTTRIUM BARIUM COPPER OXIDE (YBCO)

With the chemical formula YBa₂Cu₃O₇, yttrium barium copper oxide (YBCO) is one of the most extensively researched high-temperature superconductors. It was discovered in 1987 and may be chilled with liquid nitrogen due to its critical temperature (T_c), which is approximately 92 K (Dzul-Kifli et al. 2022; Jain et al. 2013; Sah et al. 2024). YBCO is a highly sought-after material for use in power transmission and magnetic levitation systems because of its remarkable capacity to transport enormous currents without encountering resistance (Bektas et al. 2024; Bennár et al. 2024; Li-Ye et al. n.d.). Superconducting cables in power grids would find YBCO's remarkable capacity to carry high currents to be quite suitable. Nearly little electrical resistance these cables offer helps to drastically reduce energy losses during long-distance transmission. Strong, consistent magnetic fields produced by YBCO are crucial for both levitation and propulsion, so magnetic levitation (maglev) trains also depend on it (Jiang et al. 2019; Jing et al. 2013; Yu et al. 2020). YBCO is a more reasonably priced choice than low-temperature superconductors such as NbTi because of its greater running temperature. Liquid nitrogen, a less expensive and simpler-to-manage coolant than liquid helium, can be used to chill it (Chu et al. 2022; Trabelsi et al. 2022; Yao & Ma 2021).

Because they can transmit significant currents without resistance, superconducting materials such as YBCO are indispensable in many modern technological uses. One

important usage is in power transmission, where long-distance superconducting cables derived from YBCO greatly lower energy losses. Modern power grids would benefit from these lines since they allow the effective movement of electricity (Bektas et al. 2024; Li-Ye et al. n.d.; Xia et al. 2024). YBCO is also used in maglev trains, where superconducting magnets allow the principle of magnetic levitation to lift and move the train, enabling frictionless, fast travel. Because the train and the rails do not physically touch, this technology not only increases energy efficiency but also speeds travel and lowers maintenance expenses (Jiang et al. 2019; Z. Liu et al. 2021). Moreover, YBCO is indispensable for creating high-field magnets, and it is extensively applied in laboratory research environments. Particularly in disciplines like nuclear magnetic resonance (NMR) and particle physics, these magnets—capable of producing quite strong and stable magnetic fields—are indispensable for scientific studies (Abulaiti et al. 2024; Bektas et al. 2024; Bennár et al. 2024).

BISMUTH STRONTIUM CALCIUM COPPER OXIDE (BSCCO)

With a critical temperature (T_c) of roughly 107 K, bismuth strontium calcium copper oxide (BSCCO), known by its chemical formula Bi₂Sr₂CaCu₂O₈, is another well-known high-temperature superconductor. Superconducting tapes, which are necessary for making high-field magnets and superconducting power cables, are frequently made using BSCCO (Z. Lei et al. 2023; Y.-R. Zhang et al. 2022, 2023). BSCCO is ideal for commercial applications including high-energy physics experiments and power distribution systems because it can be manufactured into long, flexible tapes (Safran et al. 2015; Y.-R. Zhang et al. 2022, 2023). These tapes, often coated with metals for mechanical strength, provide high magnetic fields needed in scientific research and advanced energy systems. BSCCO is vital to the development of superconducting fault current limiters (SFCLs), which protect electrical grids from short-circuit damage (Belkhiri & Ghemari 2022; Yonemura et al. 2015; Jiahui Zhu et al. 2023).

Its ability to be manufactured into long, flexible superconducting tapes makes BSCCO important in many applications. Superconducting power cables, which transport electricity with low energy losses over long distances, are one of its main uses. These cables boost electricity grid efficiency and capacity (Ferreira da Silva et al. 2022; Yao & Ma 2021; Y.-R. Zhang et al. 2023). BSCCO is also employed in particle accelerators, which need strong, steady magnetic fields to guide and accelerate particles. These scientific applications benefit from

BSCCO's high-field magnet production (Shen & Garcia Fajardo 2020; Y.-R. Zhang et al. 2022, 2023). BSCCO also protects electrical grids from short circuits by regulating excess currents without interrupting the power supply in superconducting fault current limiters (SFCLs) (Hobl et al. 2012; Morandi & Imperato 2009). Modern power systems are safer and more reliable with these capabilities.

DOPED AND THIN FLIM BASED SUPERCONDUCTORS (DOPED AND THIN FILM FESE)

Iron selenide (FeSe) is a notable material within the category of iron-based superconductors, especially because of its capacity to enter the domain of high-temperature superconductors (HTS) under certain conditions. Although bulk FeSe exhibits a T_c of about 8 K, studies indicate that through electron doping, the T_c can be elevated to approximately 48 K (B. Lei et al. 2016; H.-S. Xu et al. 2022; Zhou et al. 2019). Remarkably, single-layer FeSe films cultivated on substrates like SrTiO₃ can reach a T_c of up to 80 K, elevating FeSe into the high-temperature

superconductor category (Ge et al. 2014, 2015; D. Liu et al. 2012; Y. Xu et al. 2021; Shuyuan Zhang et al. 2019). The rise in T_c is thought to stem from magnetic interactions instead of traditional phonon-mediated electron pairing, positioning FeSe as a promising option for thin-film technologies and quantum computing (Feng et al. 2024; Gu et al. 2022). The capacity to attain elevated T_c values via substrate engineering positions FeSe as a highly promising candidate for applications that generally depend on high-temperature superconductors.

A comparative review of important superconducting materials, such as high-temperature superconductors (HTS) and low-temperature superconductors (LTS), is given in Table 1. Important characteristics that affect each material's practical uses and cooling needs are highlighted in this table, including the chemical formula, type, critical temperature (T_c), and critical magnetic field. Notably, whereas YBCO and BSCCO represent significant HTS advancements, materials like niobium-titanium (NbTi) and niobium-tin (Nb₃Sn) are well-established LTS possibilities. Additionally, covered is the special case of iron selenide (FeSe), which shows how its T_c varies depending on its structural circumstances.

TABLE 1. The properties of significant superconducting materials.

Superconductor	Chemical Formula	Type ^ψ	Critical Temperature (K)	Critical Magnetic Field (T)
Tin	Sn	I	3.72	0.005
Lead	Pb	I	7.19	0.015
Mercury	Hg	I	4.15	0.091
Niobium-Titanium*	NbTi	II	9.3	10-12
Niobium-Tin*	Nb ₃ Sn	II	18.1	20-25
Magnesium Diboride**	MgB ₂	II	39	20
Yttrium Barium Copper Oxide	YBa ₂ Cu ₃ O ₇ (YBCO)	II	92	0.2
Bismuth Strontium Calcium Copper Oxide	Bi ₂ Sr ₂ CaCu ₂ O ₈ (BSCCO)	II	107	0.2
Lanthanum Barium Copper Oxide	LaBaCuO (LBCO)	II	40	0.2
Iron Selenide (bulk)***	FeSe	II	8	0.17
Iron Selenide (single layer on SrTiO ₃)	FeSe/SrTiO ₃	II	~80	-

Usually, elemental superconductors (such as lead, mercury, and tin) that display superconductivity at comparatively low critical temperatures and magnetic fields are known as type I superconductors. Below this temperature (the Meissner effect), they entirely expel magnetic fields and undergo a fast transition to a superconducting state at a certain T_c . However, even moderate magnetic fields cause them to completely lose their superconductivity. Compared to Type I, Type II superconductors can tolerate substantially greater magnetic fields. These superconductors are typically compound or alloy materials (such as NbTi, Nb₃Sn, and HTS materials

like YBCO). They display a mixed state (vortex state) in which quantized flux lines allow magnetic fields to partially permeate the material. Because of this property, they can remain superconducting even in extremely high magnetic fields, which makes them crucial for applications that need high magnetic fields, such as particle accelerators and magnetic resonance imaging. Niobium-titanium (NbTi) and Niobium-Tin (Nb₃Sn) are widely recognized low-temperature superconductors, actively employed in various fields such as MRI technology and particle acceleration. Magnesium Diboride (MgB₂), with a critical temperature (T_c) of 39 K, allows for cooling through the use of liquid

hydrogen or cryocoolers, making it suitable for particular applications that require cost-effective cryogenic solutions. Iron Selenide (FeSe) in

its bulk form is typically identified as a low-temperature superconductor but is capable of demonstrating high-temperature superconductor characteristics (up to 80 K) when applied in a single-layer configuration on SrTiO₃ substrates, thereby broadening its range of potential applications.

BRIEF HISTORY OF SUPERCONDUCT MATERIALS

Major events that have affected our knowledge and application of superconductivity define the history of superconducting materials. Heike Kamerlingh Onnes initially noted the phenomena in 1912 when he found superconductivity in mercury at near absolute zero. This first finding prepared the way for later investigation on Type I and Type II superconductors, two main classifications for superconducting materials. Lead and mercury type I superconductors show perfect diamagnetism, but their low critical magnetic fields and current densities restrict their useful uses (Blaugher 1996; K. Sato 2008b). Particularly niobium-titanium (NbTi) and niobium-tin (Nb₃Sn), creating Type II superconductors was a breakthrough in the discipline. Practical uses for these materials, such as MRI machines and electromagnets in particle accelerators, fit their capacity to transport far greater currents and run in stronger magnetic fields (Blaugher 1996). These materials' arrival in the 1960s made it possible to build superconducting cables and wires, which are crucial for high-current uses (Blaugher 1996). A turning point in superconductivity research came in 1986 with identifying high-temperature superconductors (HTS), mostly superconducting ceramics. These materials run far higher than their predecessors, which makes liquid nitrogen a suitable substitute for the more costly liquid helium in cooling (Cava et al. 1987; Chu et al. 1987; Wu et al. 1987). This discovery not only broadened the spectrum of possible uses but also sparked fresh enthusiasm in the subject, which resulted in continuous investigation aiming at finding novel materials and knowledge of the mechanics underlying high-temperature superconductivity. With uses in technologies like maglev trains and particle accelerators, which use their special qualities of low electrical resistance and large magnetic fields, superconducting materials have evolved over the years in application (Ball & Goodzeit n.d.; Nagashima 2017; Yao & Ma 2021). To reach room-temperature superconductors, which would transform several sectors and daily technologies, the dynamic field of superconducting material evolution remains under active investigation (Hamlin 2019; Narayan 2024; University of

Illinois Chicago 2024). All things considered, the history of superconducting materials shows a path from the first discovery of superconductivity to the evolution of useful applications and the continuous study of fresh materials. Major developments in material science and a better knowledge of the fundamental physics of superconductivity have been driving this trend.

COMPARISON BETWEEN SUPERCONDUCTORS AND NORMAL CONDUCTORS

There are notable variations in the electrical characteristics of superconductors and conventional conductors, especially concerning resistance and energy dissipation. Joule energy losses occur when electric current flows through normal conductors like copper and aluminium because of their electrical resistance. Power distribution networks may experience significant energy loss as a result of this resistance's generation of heat (Barnes et al. n.d.; Toshiba Energy Systems & Solutions Corporation 2022; Yao & Ma 2021; Zhai et al. 2024). Superconductors, on the other hand, are substances that show zero electrical resistance and permit the unhindered flow of electricity when cooled below a critical temperature (T_c) (Persano Adorno et al. 2024; Toshiba Energy Systems & Solutions Corporation 2022; Trabelsi et al. 2022). Because of this special characteristic, superconductors may drastically lower Joule energy losses, which makes them extremely effective in transmitting and using electricity (Braginski 2019; Clynes 2023; Dean & Kunchur 2016; Ekin 2004). The phenomenon of zero power dissipation in superconductors is another important characteristic. Superconductors preserve energy during electrical transmission without losing any, in contrast to ordinary conductors, which lose energy as heat because of resistance (Mikhail I Eremets 2024; Laquer 1976; Senatore & Rivkin 2019; Yao & Ma 2021). This feature is especially helpful in applications where energy economy is crucial, including motors and power generators, where the absence of resistive heating allows for weight and size reduction (Bernstein & Noudem 2020; R. G. Sharma 2021c). When a material enters the superconducting state, magnetic field lines are expelled from it, a phenomenon known as the Meissner effect. Magnetic levitation, which is not seen in typical conductors, is made possible by this effect (Bernstein & Noudem 2020; Essén & Fiolhais 2012; Kim 2019; Kozhevnikov 2021). For applications like particle accelerators and superconducting magnets used in MRI equipment, the capacity to generate powerful magnetic fields without sacrificing energy is essential (Kutsaev 2024; Marchevsky 2021; Marchio 2024; SCMAGLEV n.d.; Yao & Ma 2021).

Additionally, the two kinds of materials have different underlying current flow mechanisms (Nikolić & Tešanović 2011; SCMAGLEV n.d.; Smith et al. 2022; Solovjov & Rogacki 2023). Contrarily, individual electrons in typical conductors often collide with impurities and lattice vibrations, resulting in resistance and energy loss. In conclusion, superconductors are appropriate for cutting-edge technological applications due to their many benefits over conventional conductors, such as their zero resistance, zero power dissipation, and special magnetic characteristics. The Meissner effect and the creation of Cooper pairs during the transition to superconductivity represent a dramatic change from the behavior of typical conductive materials. The electronic fluid of superconductors, particularly type I superconductors, is made up of bonded pairs of electrons called Cooper pairs rather than individual electrons

(Arutyunov et al. 2021; Persano Adorno et al. 2024; Solovjov & Rogacki 2023). The exchange of phonons between electrons creates an attractive force that leads to this pairing. According to quantum mechanics, this Cooper pair fluid's energy spectrum has an energy gap, which indicates that a minimum quantity of energy ΔE is required to excite the fluid (John Bardeen 1973b; A. Yang et al. 2024; C.-K. Yang & Lee 2023). Therefore, the fluid will not be scattered by the lattice if ΔE is more than the thermal energy of the lattice kT , where T is the temperature and k is Boltzmann's constant. Because of this, the Cooper pair fluid is superfluid, which means it may flow with zero resistance and no energy loss (CCAS 2024; F. Smith & P. Slichter 2006). Figure 2 (Keysan 2013) shows the resistance of conventional conductors and superconductors as a function of temperature.

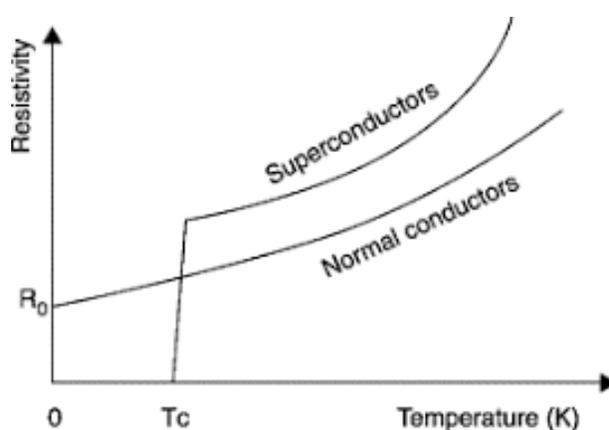


FIGURE 2. Resistance versus temperature curve of superconductors and normal conductors (Keysan 2013).

TYPES OF SUPERCONDUCTORS

Superconductive materials are classified into various categories based on their operational temperatures and properties, notably including high-temperature superconductors (HTS), low-temperature superconductors (LTS), and conventional superconductors. HTS, such as cuprate superconductors, operate above 77 K, making them advantageous for applications in power systems and

electronics, while LTS, like niobium-titanium alloys, function below 30 K and are used in superconducting magnets. Conventional superconductors, including magnesium diboride, are defined by BCS theory and serve specific applications, such as in MRI machines and particle accelerators, due to their lower critical temperatures. In table 2 given some materials and their critical temperature for example.

TABLE 2. Critical temperatures, cooling media, and key applications of some LTS and HTS.

Material	Type	Critical Temperature (T_c)	Cooling Requirement	Critical current density	Magnetic field tolerance	Key Applications
Niobium-Titanium (NbTi)	LTS	9.3 K	Liquid Helium	$\sim 3 \times 10^5$	~ 10 T	MRI, Particle Accelerators
Niobium-Tin (Nb_3Sn)	LTS	18.1 K	Liquid Helium	$\sim 1 \times 10^5 - 2 \times 10^5$	~ 20 T	Fusion Reactors, MRI

continue ...

... cont.

Material	Type	Critical Temperature (T _c)	Cooling Requirement	Critical current density	Magnetic field tolerance	Key Applications
Yttrium Barium Copper Oxide (YBCO)	HTS	92 K	Liquid Nitrogen	~1×10 ⁶	>30 T	Power Transmission, Maglev Trains
Bismuth Strontium Calcium Copper Oxide (BSCCO)	HTS	107 K	Liquid Nitrogen	~1×10 ⁵	~15–25 T	Power Distribution, SFCLs

Materials exhibiting zero electrical resistance and magnetic field expulsion below a specified threshold temperature known as the superconducting transition temperature (T_c) are called superconductors. Their physical characteristics, critical temperatures, and underlying mechanisms help one to classify them generally into numerous forms. The several kinds of superconductors are discussed in this response together with their special features and uses.

TYPE-I AND TYPE-II SUPERCONDUCTORS

Type I superconductors are usually pure elemental superconductors, these show total magnetic field expulsion—the Meissner effect—below their critical temperature. Their single critical magnetic field over which superconductivity is eliminated is Because of their low critical magnetic fields, type I superconductors have a lengthy coherence duration and are usually not used in high-field applications (Sundahl et al. 2021b; Valente-Feliciano et al. 2022). Most alloy and compound superconductors fall within type II superconductors. Bc1 and Bc2 are two important magnetic fields they display. They enable partial penetration of magnetic fields in the form of quantized vortices between these domains, hence preserving superconductivity in a mixed state. Maglev trains and MRI machines are two technical uses for Type II superconductors since they can transport enormous currents in high magnetic fields (Haack 2024).

HIGH-TEMPERATURE SUPERCONDUCTORS (HTS)

Although low-temperature superconductors are indispensable in high-field applications, their reliance on liquid helium cooling limits their general use. The field was transformed when high-temperature superconductors

(HTS) were discovered in the 1980s (Bednorz & Mueller 1986; Chu et al. 1987; Wu et al. 1987) since these materials showed superconductivity at temperatures much above those predicted by the BCS theory, creating new industrial uses with more easily available cooling methods, such as liquid nitrogen. Cuprates and iron-based superconductors among HTS materials conduct electricity at rather higher temperatures than LTS (Barišić & Sunko 2022; Keimer et al. 2014; Wesche 2025). Popular HTS materials are yttrium barium copper oxide (YBa₂Cu₃O₇) or YBCO and bismuth strontium calcium copper oxide (Bi₂Sr₂CaCu₂O₈) (Abdul Hussein et al. 2023; Bektas et al. 2024; Khallouq 2024; Namburi et al. 2021). Their critical temperatures exceeding 77 K both allow liquid nitrogen to boil. This discovery has changed superconducting technology since liquid nitrogen is less expensive and more practical than liquid helium, which cools LTS materials (“A quantitative description of high-temperature superconductivity” 2023; Molodyk & Larbalestier 2023; Yuxue Wang et al. 2023). With some reaching above 100 K, these materials and iron-based superconductors have critical temperatures above 30 K. Class II superconductors typically have complex crystal structures and unique superconducting processes. They are often used in situations where cooling to extremely low temperatures is impractical (Naskar et al. 2021; Puphal et al. 2024; Romano et al. 2024; Temple 2022).

LOW-TEMPERATURE SUPERCONDUCTORS (LTS)

After establishing the Bardeen-Cooper-Schrieffer (BCS) theory as the theoretical foundation for superconductivity, it is evident that low-temperature superconductors (LTSs)—the first class of superconducting materials to be discovered—are the most immediately affected by the theory. The BCS theory predicts that these conventional superconductors, like niobium (Nb), lead (Pb), and niobium-tin (Nb₃Sn), will behave as expected when superconductivity is present at temperatures below 20 K.

Comprehending the characteristics and uses of these substances is essential to realizing the technological progress enabled by low-temperature superconductivity. LTSs conduct electricity at nearly zero degrees Celsius (Alade et al. 2022; Hegg et al. 2024; Trabelsi et al. 2022). They normally work below 20 K. Bardeen-Cooper-Schrieffer's (BCS) theory explains everything about these materials. According to it, superconductivity is enabled by Cooper pair creation. LTS materials include Nb, Ti, Al, and Sn. Niobium-titanium (NbTi) (Guo et al. 2018; Patel et al. 2019), Nb₃Al (X. Chen et al. 2022; Tsapleva et al. 2022), and Nb₃Sn (Banno et al. 2021a; Tsapleva et al. 2022; Williams 2024) are common combinations. Magnesium diboride (MgB₂) is another crucial LTS material. Its critical temperature (T_c) is 39 K, which allows it to work at higher temperatures than most LTS materials, but it still needs cryogenic cooling (Bekaert et al. 2017; Fluekiger 2016; Krinitsina et al. 2021; Putti & Grasso 2011; S. Wang 2003).

The most widely utilized and studied LTS materials are NbTi and Nb₃Sn. Both are needed to create powerful magnetic fields at low temperatures, making them crucial for high-tech usage. MRI equipment, particle accelerators, and study labs use these materials. Superconductivity requires a lot of cooling, usually using liquid helium. Despite being less powerful than NbTi or Nb₃Sn, magnesium diboride (MgB₂) has a higher T_c and requires less cooling, making it a viable candidate for liquid hydrogen or cryocoolers (Prikhna et al. 2024; Stautner et

al. 2014). MgB₂ is ideal for creating affordable superconducting power connections and studying tiny magnets (Bekaert et al. 2017; Krinitsina et al. 2021; Putti & Grasso 2011).

These include conventional superconductors, such as niobium-titanium, which are used in devices like particle accelerators that require high magnetic fields. They typically have critical temperatures below 30 K and require liquid helium for cooling 26K. Low-Temperature Superconductors (LTS), such as NbTi and Nb₃Sn, face significant cooling challenges due to their requirement for liquid helium operation at temperatures around 4.2 K. This makes systems costly and dependent on a scarce cryogen. Additionally, mechanical brittleness, especially in Nb₃Sn, limits flexibility during fabrication and usage. LTS materials also have moderate critical magnetic field and current density limits, which constrain their performance in high-demand applications.

Their critical current density (J_c) is often anisotropic, meaning it degrades in certain magnetic field orientations. Additionally, the high cost of production, due to complex coating or deposition processes, remains a major barrier to large-scale adoption. Table 3 presents a concise comparison between Low-Temperature Superconductors (LTS) and High-Temperature Superconductors (HTS) by highlighting their key technical challenges and the most promising engineering or material-based solution.

TABLE 3. Key challenges and proposed solutions for both LTS and HTS materials

Type	Challenge	Proposed Solution
LTS (NbTi, Nb ₃ Sn)	Requires ultra-low temperatures (~4.2 K, liquid helium), increasing cost and system complexity	Use of closed cycle cryocoolers, helium re-liquefaction, and recycling systems
	Mechanical flexibility is limited in Nb ₃ Sn (brittle under stress)	Wind-and-react technique; pre-strain optimization during fabrication
	Helium is expensive and increasingly scarce	Integration of helium recovery systems and advanced insulation
	Moderate critical current and field tolerance (10–20 T max)	Alloying & composite wire development to improve J _c and B _{c2}
HTS (e.g., YBCO, BSCCO)	Brittle and anisotropic ceramic structure makes handling and winding difficult	Use of 2G REBCO tapes with metallic substrates & buffer layers
	Still needs cooling (liquid nitrogen or cryocoolers), though less demanding than helium	Develop ambient-pressure superconductors, improve thermal insulation
	High production cost due to complex fabrication processes (e.g., pulsed laser deposition)	Scaling up low-cost deposition methods (e.g., MOD, CSD)
	J _c is highly dependent on crystal alignment and magnetic field orientation	Use nanoparticle pinning and biaxially textured substrates to stabilize J _c

CONVENTIONAL AND UNCONVENTIONAL SUPERCONDUCTORS

Bardeen-Cooper-Schrieffer (BCS) theory explains conventional superconductors by characterizing superconductivity as the product of electron pairing mediated by lattice vibrations (phonons). This group includes most elemental superconductors as well as several alloys (Seidel 2015b). High-temperature cuprates and iron-based superconductors are classified as unconventional superconductors. Their pairing mechanisms remain unclear, possibly involving magnetic interactions or other exotic processes. These materials often display unusual characteristics and complex phase diagrams (Braginski 2019).

OTHER CATEGORIES

Iron-based superconductors, discovered in the 2000s, have gained significant attention due to their relatively high critical temperature (T_c) and potential applications in everyday life. They are considered unconventional and exhibit a variety of magnetic and structural phases (Hou et al. 2023; P. D. Johnson et al. 2015; P. Yang et al. 2024). Topological superconductors are defined by unique surface states that are protected by topological invariants. Their ability to host Majorana fermions makes them particularly intriguing for quantum computing applications (J. Bardeen et al. 1957b; Leijnse & Flensberg 2012; M. Sato & Ando 2017; M. M. Sharma et al. 2022). Superconductors with non-centrosymmetric structures lack a center of symmetry, resulting in mixed spin-singlet and spin-triplet pairing states. This provides insight into how spin-orbit coupling interacts with superconductivity (J. Bardeen et al. 1957a; Bauer & Sigrist 2012; Kapustin & Radzihovsky 2022; Naskar et al. 2021). Although the categorization of superconductors offers a structure for comprehending their several characteristics and uses, fresh materials and phenomena are still being found by continuous investigation. Particularly in energy-efficient systems and quantum technologies, this dynamic field shows potential for further technical developments.

The efficacy attributes of materials utilized in superconductivity are delineated by numerous pivotal parameters that ascertain their appropriateness for practical implementations. A foremost attribute is the critical temperature (T_c), which signifies the temperature threshold below which a material manifests superconducting behavior. For instance, low-temperature superconductors (LTS) such as NbTi and Nb₃Sn function at temperatures below 10–20 K, whereas high-temperature superconductors

(HTS) like YBCO and BSCCO exhibit superconductivity at temperatures exceeding 77 K, permitting cooling via liquid nitrogen, a process that is markedly more cost-effective. Another crucial performance criterion is the critical current density (J_c), which indicates the maximum current that a superconductor can transit without relinquishing its superconducting characteristics. HTS materials generally present elevated J_c values in zero magnetic fields; however, their efficiency is frequently susceptible to external fields and anisotropic effects. Conversely, LTS materials display more consistent J_c behavior when subjected to magnetic fields, although they are constrained by lower T_c values.

The tolerance to magnetic fields, commonly referred to as the upper critical field (B_{c2}), represents another essential performance metric, particularly for applications such as MRI equipment and particle accelerators. HTS materials, especially those based on REBCO tapes, can sustain superconductivity in magnetic fields that exceed 30 T, thus eclipsing the capabilities of traditional LTS materials. Additionally, mechanical and thermal stability are paramount in practical applications. While LTS materials such as NbTi exhibit ductility and can be readily manufactured into wire formats, HTS materials tend to be intrinsically brittle and necessitate intricate multilayer structures to improve flexibility and resilience. Moreover, the behaviour concerning AC losses, thermal conductivity, and quench propagation characteristics significantly influences the reliability and energy efficiency of superconducting systems.

IMPORTANT OF EXCEPTIONAL SUPERCONDUCTORS

The remarkable characteristics of superconductors, especially their zero electrical resistance and the Meissner effect, play a crucial role in the progression of numerous technologies and applications. Superconductivity enables materials to transmit electricity without resistance when cooled below a critical temperature, resulting in nearly 100% efficiency in electrical transmission (Blaugher 1996; University at Buffalo 2024b). This feature greatly minimizes energy losses, essential for power distribution systems, since conventional conductors lose energy as heat because of resistance (Q. Chen et al. 2024; Kozhevnikov 2021; Mercer & Pashkin 2023; R. G. Sharma 2021a). Furthermore, zero resistance facilitates the advancement of superconducting detectors, which play a crucial role in areas like quantum computing and medical imaging. These detectors utilize the distinctive characteristics of superconductors to attain exceptional sensitivity and

efficiency, rendering them essential in applications such as MRI machines and particle accelerators (Esmaeil Zadeh et al. 2021; Gérard et al. 2018; Hays 2021). One notable characteristic of superconductors is the Meissner effect, which entails the expulsion of magnetic fields from the material. This phenomenon facilitates magnetic levitation and is a crucial criterion for recognizing superconducting states (Hirsch 2013; Kozhevnikov 2021; Wen 2022). Levitation of magnets presents significant applications in transportation technologies, exemplified by magnetic levitation trains that function with diminished friction and enhanced velocities. Cooper pairs, the electron pairs that traverse a superconductor in unison, are fundamental to grasping the phenomenon of superconductivity. These pairs enable current flow without resistance, which is crucial for sustaining the superconducting state (Alade et al. 2022; CERN 2024a; Mikhail I Eremets 2024). The stability of these pairs under varying conditions is essential for advancing room-temperature superconductors, which, if found, could transform various technologies by removing the necessity for cryogenic cooling. Moreover, the critical current density of superconductors determines the highest current they can transport while maintaining their superconducting characteristics. This feature is essential for the design of superconducting magnets and various applications that demand high current densities (John Bardeen 1973a; Blair & Hampshire 2022; Chaddah 2003;

Tsapeleva et al. 2022). In conclusion, the remarkable characteristics of superconductors—zero resistance, the Meissner effect, and the formation of Cooper pairs—are essential for comprehending superconductivity and propelling advancements in numerous technological fields. Their ability to improve energy efficiency and facilitate advanced applications highlights the significance of continuous investigation in this area (Kozhevnikov 2021; Mercer & Pashkin 2023; Mo et al. 2024).

APPLICATIONS

The practical uses of traditional superconductors are constrained by their extremely low operating temperatures. The identification of materials with elevated critical temperatures broadens the potential uses of superconductors. These applications encompass high-speed trains, magnetic energy storage, magnetic resonance imaging (MRI) for medical purposes, Josephson devices, superconducting quantum interference devices (SQUID), magnetoencephalography, microwave devices, and resonators utilized in high-energy physics experiments (Mikhail I Eremets 2024; Han et al. 2024; L. Yang et al. 2024). Figure 3 showing exclusively on a superconductor applicable to electric power, transportation, telecommunication, and medicine.

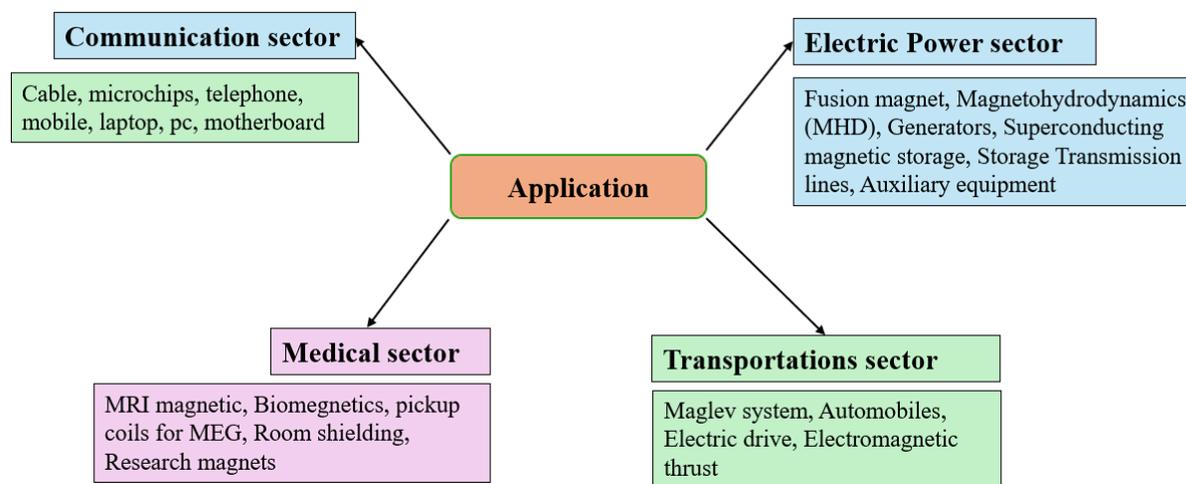


FIGURE 3. Application of superconducting materials

ELECTRIC POWER SECTOR

Superconducting materials have arisen as a revolutionary technology in electric power applications owing to their distinctive features, including low electrical resistance and

elevated current-carrying capacity. These materials are included in several elements of the power grid, providing substantial enhancements in efficiency and performance. This document examines the principal applications and advantages of superconductors in electric power systems,

along with the associated obstacles and prospective developments for this technology. SMES systems employ superconductors to store energy within the magnetic field generated by the flow of direct current. These systems exhibit excellent efficiency, characterized by quick response times and negligible energy loss, rendering them optimal for stabilizing power grids and supplying backup power during peak demand (Arutyunov et al. 2021; Ferreira da Silva et al. 2022; Hassenzahl et al. 2004; Jiamin Zhu et al. 2022). Superconducting fault current limiters (SFCLs) are essential for safeguarding power systems against elevated short-circuit currents, which may surpass operating thresholds by over tenfold. SFCLs restrict these currents without severing the system, hence improving grid dependability (Alam et al. 2018; Attard 2022; Brown University 2019; Gray & Fowler 1978; V et al. 2016). High-temperature superconductors (HTS) are especially advantageous for superconducting fault current limiters (SFCLs) since they function effectively at elevated temperatures, such as those attainable with liquid nitrogen, hence minimizing cooling expenses and complexities. Superconducting cables provide elevated throughput with less electrical losses, facilitating more efficient power transfer across extensive distances. This may result in significant energy conservation and enhanced capacity in power systems (Attard 2022; Naskar et al. 2021; Peng et al. 2022; Vyatkin et al. 2015). The advancement of HTS wires, which merge high current-carrying capacity with mechanical robustness and flexibility, is essential for their use in commercial power initiatives (K. Sato 2007; Wimbush 2020; Yamada 2024).

TRANSPORTATION SECTOR

Superconducting materials exhibit considerable potential to transform transportation applications, attributed to their distinctive characteristics, including zero electrical resistance and magnetic field expulsion. The characteristics facilitate the creation of efficient, high-speed, and environmentally sustainable transportation systems. This document examines the diverse applications of superconductors in transportation. Superconductors have the potential to markedly decrease energy losses in electric vehicles, thereby enhancing their efficiency and environmental sustainability. High-temperature superconductors (HTS) exhibit significant potential owing to their capacity to function at elevated temperatures, thereby minimizing the necessity for elaborate cooling systems. The use of liquid hydrogen as both a fuel and a coolant enhance this system, negating the necessity for separate cooling devices (Böer & Pohl 2023; M. I. Eremets

et al. 2022; Mikhail I Eremets 2024; Z. Zhang et al. 2022). Maglev trains represent a significant implementation of superconducting technology within the transportation sector. Superconducting magnets enable these trains to levitate above the tracks, minimizing friction and facilitating high-speed travel with reduced power consumption. This technology is efficient, environmentally friendly, and safe (Aguilera-Navarro et al. 1991; L. R. Johnson et al. 1989; H. Li et al. 2023; Nagashima 2017). Superconducting conductor arrangements in maglev systems enable the concurrent operation of power supply and electromagnetic levitation, optimizing infrastructure costs (~anzara' et al. 2003; Fujie 1991; Nagashima 2017). The integration of superconducting transmission lines with transportation systems, exemplified by the proposed Super-MAGLEV, has the potential to transform energy transfer and transportation modalities significantly. This system proposes a network utilizing superconducting cables and ultra-fast trains within vacuum tunnels, potentially achieving speeds of 2000 miles per hour (~anzara' et al. 2003; Chowdhury & Sahoo 2023; Nagashima 2017). The integration of a hydrogen economy with superconducting technology may facilitate efficient energy storage and transfer, thereby improving the feasibility of these systems (Gan et al. 2024; Mojarrad et al. 2022; Trabelsi et al. 2022).

COMMUNICATION SECTOR

Superconducting materials exhibit considerable promise to transform communication technologies owing to their distinctive characteristics, including low electrical resistance and magnetic field expulsion. These attributes facilitate the advancement of sophisticated communication systems with improved performance and efficiency. Superconductors are being investigated for extremely low frequency (ELF) communication, especially in undersea communication systems. Superconducting antennas have benefits compared to conventional antennas, including enhanced signal reception and diminished size, which are essential for underwater communication (Hegg et al. 2024; Oda et al. 2007; Ohnuma et al. 1994). High-temperature superconductors (HTS) are employed in satellite communications to produce low-loss components such as beamforming networks, delay lines, and phased array antennas. These components augment the efficacy of satellite systems by minimizing signal attenuation and enhancing data transfer capabilities. High-temperature superconductors are being incorporated into telecommunications to enhance the efficacy of microwave circuits and waveguides. These materials provide reduced surface resistance and enhanced conductivity, crucial for

effective signal transmission in communication networks (Alade et al. 2022; Hayakawa & Koshizuka 1992; Mansour 2001). Research is actively progressing in the development of superconducting waveguides and related components, concentrating on addressing the constraints of current models and enhancing electromagnetic compatibility. Superconducting materials are essential for the advancement of sophisticated electronic components, including filters, resonators, and transistors. These elements are essential for rapid data processing and communication systems. Superconducting single-photon detectors are being developed in quantum communication to improve the security and efficiency of quantum information systems. These detectors utilize the distinctive characteristics of superconductors to attain improved sensitivity and minimal noise levels (Esmaeil Zadeh et al. 2021; Gérard et al. 2018; Patel et al. 2019; You 2020).

MEDICAL SECTOR

Offering major developments in diagnosis imaging, treatment, and drug delivery systems, superconducting materials have transformed many medical uses. High-performance medical technologies owe their development to these materials, which are distinguished by their low-temperature conductivity of electricity free of resistance. MRI devices depend critically on superconducting magnets since they produce strong magnetic fields required for detailed imaging (Shang et al. 2024). Because low-temperature superconductors (LTS), like NbTi wires, can effectively create strong magnetic fields, they are increasingly used in commercial MRI systems (Yulin Wang et al. 2023). With great sensitivity, these methods use SQUIDS to detect the magnetic fields generated by heart and neural activity, therefore providing non-invasive diagnostic possibilities. External beam therapy targets malignant tissues exactly using protons and carbon ions in compact superconducting cyclotrons (Moszlige et al. 2005). Medical facilities find these cyclotrons useful since their smaller size and lower cost make them more easily available. Medical isotopes are also produced with ease using superconducting magnets in cyclotrons; these are vital for many diagnostic and treatment processes (Alrashdi et al. 2024; X. Chen et al. 2022). The navigation of ferromagnetic particles in the bloodstream is regulated by superconducting magnets, so improving the accuracy of drug distribution to certain body regions. This approach reduces adverse effects and increases the effectiveness of therapies (Tsapleva et al. 2022; Zhao & Shi 2023).

Superconducting materials are revolutionizing multiple industries with their unique ability to conduct

electricity without resistance and expel magnetic fields. In the electric power sector, they offer ultra-efficient transmission, high-capacity power cables, fault current limiters, and compact transformers. Real-world implementations like the *AmpaCity project* in Germany and *SFCL deployment in Korea* demonstrate their growing practicality, though high cooling costs and brittle materials remain challenges. In the transportation sector, superconductors enable magnetic levitation (maglev) trains, lightweight electric motors, and ship propulsion systems. Japan's SCMaglev and the U.S. Navy's HTS propulsion trials highlight the potential, albeit with significant infrastructure and cryogenic hurdles.

In the communication sector, superconductors provide ultra-low loss filters, high-frequency resonators, and components for quantum communication systems. These are particularly valuable in aerospace, with NASA using superconducting receivers in satellite links. However, widespread terrestrial use is limited by fabrication complexity and cooling requirements. Finally, in the medical field, superconductors are foundational to technologies like MRI machines, MEG brain scanners, and cyclotrons for cancer therapy. They offer unmatched magnetic stability and precision, with HTS variants promising lower maintenance and helium-free designs. Medical applications are currently the most mature, but ongoing advances continue to improve accessibility and performance across all sectors.

CONCLUSION

While significant strides have been made in the quest to identify new high-temperature superconductors, parallel initiatives have also been undertaken to elucidate the fundamental characteristics of these intriguing materials. Future research must place a strong emphasis on the synthesis of exceptionally high T_c materials. Innovative synthesis techniques must be developed to transition from current laboratory methods to more industrially viable processes. Moreover, additional efforts are required to address the current limiting mechanisms in high-temperature superconductors and to explore potential materials-based solutions. It is widely acknowledged that both grain boundaries and flux line dynamics represent two critical limiting factors; thus, it is essential to address these challenges at the nanometre scale.

This review has explored the advancements, unique properties, and diverse applications of superconducting materials, specifically low-temperature (LTS) and high-temperature superconductors (HTS). The exceptional characteristics of superconductors, such as zero electrical

resistance and the Meissner effect, have positioned them as transformative materials in fields including electric power, healthcare, transportation, and communications. While LTS materials like NbTi and Nb \square Sn remain essential in high-field applications, the dependence on liquid helium cooling limits their broader adoption due to cost and logistical challenges. In contrast, HTS materials, particularly YBCO and BSCCO, have introduced new possibilities by operating at temperatures that allow liquid nitrogen cooling, an affordable and practical option. This development has expanded the commercial viability of superconductors in high-efficiency power transmission, maglev transportation, and other innovative applications. Despite the progress, several challenges remain, particularly regarding the scalability of HTS materials, production costs, and the need for advanced cryogenic solutions to make these materials more accessible for widespread industrial application.

The review delineates the comparative merits and drawbacks of low-temperature superconductors (LTS) and high-temperature superconductors (HTS), elucidating their pivotal contributions across diverse domains including energy and healthcare. It highlights recent technological advancements aimed at enhancing performance, emphasizing the implications of material properties and production methodologies on their practical applications.

superconducting materials both low-temperature and high-temperature variants has been substantial, several research gaps and limitations remain that must be addressed to realize their full technological potential. One major gap lies in the scalability and cost-efficiency of high-temperature superconductors (HTS). Despite their operational advantages at liquid nitrogen temperatures, their brittle ceramic nature, anisotropic properties, and high fabrication costs hinder widespread industrial adoption. For low-temperature superconductors (LTS), the primary limitation continues to be the dependence on liquid helium, which poses both economic and logistical challenges, especially in large-scale or mobile applications. Furthermore, the field lacks standardized long-term performance metrics, particularly under real-world stressors such as mechanical strain, magnetic flux creep, and thermal cycling.

Looking forward, research continues to focus on increasing critical temperatures and ultimately achieving room-temperature superconductivity. This breakthrough could revolutionize technology by eliminating the need for cryogenic cooling, thereby making superconductors more practical for everyday applications across industries. Realizing this goal requires interdisciplinary research and collaboration across scientific and industrial fields. This review underscores the potential of superconducting materials to catalyse significant advancements and

highlights the importance of continued exploration to harness the full potential of these materials.

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DECLARATION OF COMPETING INTEREST

None.

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