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Editorial

Superconducting materials – tools to combat with climate change

In response to the urgent global need to combat climate change, we are excited to explore breakthroughs in material technologies, particularly high-temperature superconductors. Our focus is on their significance in designing applications that help propel our technique towards a sustainable future. The successful application of high-temperature superconductors is delimited by critical temperature (T_c), upper critical field (B_{c2}), and current density (J_c). Due to significant relaxation effects, the applicability of high-temperature superconductors is often limited by the irreversibility boundary, in terms of magnetic fields by B_{irr} rather than B_{c2}, $B_{irr} << B_{c2}$. Increase of pinning force can significantly advance use of high-temperature superconductors' application towards real-life. A crucial factor for many applications is that B_{irr} is lowest when the magnetic field is parallel to the *c*-axis. Relaxation and, consequently, B_{irr} are influenced by the operating temperature and by effectiveness of pinning at this temperature. This editorial aims to highlight some of the advances in the development of superconducting materials and their importance in addressing the pressing challenges posed by *climate change*. Moreover, it aims to present potential solutions through innovative developments in superconducting materials.

In this comprehensive editorial, we explore the transformative potential of superconducting materials, particularly in their pivotal role in advancing global sustainability and ushering in an era of environmentally friendly energy solutions. Our exploration encompasses not only the evolution of these materials but also their profound significance in mitigating the repercussions of climate change. Central to our discourse is the multifaceted application of superconducting materials in energy transmission and storage. By harnessing the unique properties of superconductors, we have the opportunity to revolutionize the way energy is generated, stored, and distributed.

A cornerstone of this technological revolution was laid in 1986 when Müller and Bednorz discovered that the copper-based ceramic material, $(La,Ba)CuO_4$, could become superconductive, moreover at higher temperatures than the metallic superconductors known at that time [1]. Following this, another discovery by Chu et al. successfully demonstrated that replacing lanthanum with yttrium to create $YBa_2Cu_3O_y$ (YBaCuO) resulted in a superconducting onset transition temperature of 93 K, which is above the boiling point of liquid nitrogen [2]. This marked a turning point, prompting substantial efforts to harness these ceramic superconductors for super-magnet applications. However, it was realized that these materials could not be effectively used in high-field applications at the relatively inexpensive temperature of liquid nitrogen, as their irreversibility field was around 3–5 T at 77.3 K. Further efforts focused on LRE-$Ba_2Cu_3O_y$ (LRE: Nd, Sm, Eu, Gd) materials and the advancement of the oxygen-controlled melt growth process, but these did not result in a substantial increase in the irreversibility field.

Another discovery occurred with the substitution of yttrium by a mixture of the lanthanides Nd:Eu:Gd in a ratio of 33:38:28, which increased the irreversibility field (H_{irr}) to approximately 15 T at the more economical liquid nitrogen temperature. Structural analysis using a transmission electron microscope (TEM) and dynamic force microscope (DFM) showed the modulation of superconducting matter and nano-twin formation (see Fig. 1, inner ring) [3]. The high magnification scanning tunneling microscopy (STM) revealed that the nanotwins consist of rows of aligned clusters, each 3 to 4 nm in size, close to the coherence length of YBaCuO-derived compounds at 77 K. These new pinning centers have significantly enhanced B_{irr} at 77 K, marking the highest irreversibility reported to date for high T_c superconductors at this temperature. This enhancement has opened the door to numerous industrial applications, including powerful magnets for fusion, improved transportation systems, advanced medical tools, space applications, and more (see Fig. 1, outer ring).

The concept of achieving levitation using liquid oxygen has long been a cherished goal within the superconductivity community. A new type of nanometer-scale pinning medium, below 50 nm in size, was discovered and dispersed in the $(Nd_{0.33}Eu_{0.33}Gd_{0.33})Ba_2Cu_3O_y$ matrix [4]. Structural examination revealed that these novel pinning entities, ranging from 20 to 50 nm in dimension (see Fig. 1, inner ring), extended the threshold operational temperature from liquid nitrogen (77.3 K) to liquid oxygen (90.2 K). Marking a milestone, the super-current density at 90.2 K achieved 40 kA/cm^2, meeting the requisite criterion for levitation for the first time. This development opens up possibilities for real-world applications, including medicine and space programs. Liquid oxygen (LOX) is widely used as a liquid oxidizer in spacecraft applications. Typically, it is combined with liquid hydrogen or kerosene. LOX remains in active use today across various space agencies worldwide, including NASA, the European Space Agency, JAXA (Japan), and ISRO (India).

Furthermore, scientists have successfully developed cost-effective batch production methods for YBaCuO and LREBaCuO type materials, a significant advance in production techniques. This achievement has led to securing a new Japanese patent [5] and widespread adoption by numerous commercial enterprises. The successful constuction of a

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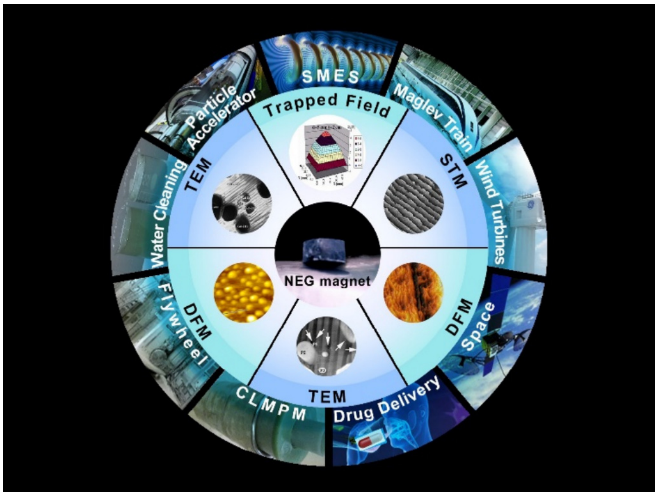

Fig. 1. Discovery of ternary LREBaCuO systems: Highlights a new class of high density nanometer pinning centers, with dimensions comparable to the coherence length, which significantly alter the properties of ternary LREBaCuO system. These alterations facilitate their use in high magnetic fields up to 15 T at 77.3 K and temperatures as high as 90.2 K. The central figure illustrates these enhanced properties, while the outer figure emphasizes the emerging applications.

high-T_c superconducting prototype MAGLEV (magnetic levitation) vehicle using batch-processed bulk GdBaCuO cryo-magnets suggests that future MAGLEV systems could operate at inexpensive liquid nitrogen temperatures. On January 13, 2021, Southwest Jiaotong University in Chengdu introduced the world's first high-temperature superconducting high-speed MAGLEV engineering prototype combined with the test line.

Developments are showcasing batch production of melt-processed YBaCuO, GdBaCuO, and (Nd,Eu,Gd)BaCuO. YBaCuO proves to be an excellent material for interacting with permanent magnets, while GdBaCuO exhibits higher performance compared to YBaCuO. Commercially produced levitation mixtures, crafted using bulk magnets by the LevMixer company, are used in water cleaning equipment, drug delivery systems, and a compact, lightweight, mobile permanent magnet system.

Innovation in ErBaCuO thick film technology for use on silver substrates marks the inception of a novel category of YBaCuO-derived silver sheets. This new discovery has been patented and used to make the world's first ErBaCuO type silver sheet wire. Additionally, superconducting cables made using materials like $Bi_2Sr_2Ca_2Cu_3O_y$ or $Bi_2Sr_2Ca_1$-Cu_2O_y, are formed into tapes with silver sheaths and require cooling below −196 °C, achieved by circulating liquid nitrogen through them.

Engineers and scientists confirm that these cables can carry much larger currents compared to traditional copper cables. However, it may take several years for power transmission and distribution to become practical as the technology matures and becomes more cost-effective, making it suitable for various industrial and everyday applications. In the upcoming years, DC HTS cables will be utilized to efficiently transmit renewable energy, particularly solar power, from regions with 365 days of sunshine to colder countries. Superconducting technology, especially supermagnets and cables, is crucial for solving energy issues and ensuring a sustainable future for the next generations.

Recent advancements in the production of long-length, high-performance coated conductor REBaCuO tapes are revolutionizing clean energy generation. Integrating high-temperature superconducting (HTSC) coils into wind turbines or generators enables the generation of clean energy and offers unprecedented capabilities in SMES energy storage, since superconductors can sustain large currents, in turn able to store magnetic energy in the form of persistent currents. These coils can store vast amounts of renewable energy, helping to overcome the intermittency challenges inherent in solar and wind power. Furthermore, HTSC cables play a crucial role in urban environments where energy density is essential. By addressing challenges such as space constraints, energy efficiency, and grid reliability, HTSC cables significantly benefit urban power systems, promoting more sustainable and resilient cities.

In today's rapidly evolving landscape, there is a notable shift towards harnessing cutting-edge technologies, particularly in offshore wind farms within power systems. These advancements promise not only more efficient power generation but also significant cost savings compared to traditional renewable energy methods. What's truly exciting is the eco-friendly nature of these systems, as they leverage innovative materials like YBaCuO-derived superconductors for wire production. Significant strides have been made in superconducting wire production, marking a pivotal moment for the future of day-to-day applications. DC superconducting cables represent a significant advancement in power transmission and transportation. Recently, Japan Railways successfully utilized a 300-meter DC superconducting cable in place of catenary wires and conducted a successful train run test. The goal of using DC superconducting cables is to combine them with renewable energy, offering numerous benefits such as load leveling, energy savings, and environmental friendliness.

Efforts to produce kilometers of versatile superconducting tapes are set to revolutionize global energy demands and promote a greener planet. This exciting journey towards sustainable energy hinges on cost-effective production of high-performance material. Low-cost, high-performance superconducting materials are essential for widespread adoption, with high-performance critical current materials being crucial for superconducting applications. Ongoing advancements promise to enhance the efficiency of superconducting systems, paving the way for their integration into mainstream energy infrastructure.

The objective of this editorial is to explore the pivotal role that the development of superconducting materials plays in fostering global sustainability and integration as a fundamental pillar of the green energy revolution. Advancements in high-T_c superconducting materials hold profound significance, particularly in establishing low-cost fabrication pathways and production methodologies. These innovations are poised to revolutionize everyday applications, ensuring their safety while concurrently bolstering efforts to nurture a more environmentally sound and sustainable planet. By embracing these advancements, we can pave the way towards a future where green technologies not only thrive but also become indispensable components in safeguarding our planet for generations to come.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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