Short report

Superconductivity Research in Turkey

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An overview of the results obtained in Turkish Universities and research centers in the field of theoretical and experimental study of newly discovered superconducting compounds is presented.

Keywords: superconductivity; fundamental properties; application.

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1. Introduction

Since its discovery, superconductivity has emerged as a transformative technology with the potential to enhance our quality of life significantly. Despite over a century of intensive research, many aspects of superconductivity remain scientifically enigmatic, posing challenges in understanding its mechanisms and advancing its applications. Superconducting materials offer a broad spectrum of applications, ranging from improving the efficiency of traditional electrical systems to enabling breakthroughs in cutting-edge technologies. These include high-speed supercomputers, magnetic field sensors (such as SQUIDs used in magnetoencephalography and magnetocardiography), superconducting analog-to-digital converters (critical for telecommunications and satellite technologies), and advanced radiation detectors. Other applications span energy storage systems (SMES), MagLev trains, powerful electromagnets for research facilities (CERN, ITER), fault current limiters (SFCL), power transmission systems, wind turbines, and hydrogen level sensors.

However, the widespread adoption of superconductivity faces challenges, including the high cost of production, the need for cooling systems to maintain extremely low temperatures, and the development of scalable and robust superconducting materials. Addressing these hurdles is crucial for realizing the full potential of superconducting technology, especially as the demands of Industry 4.0 call for more efficient and advanced systems.

In Türkiye, the field of superconductivity has garnered significant attention, with a growing number of researchers contributing to advancements in the science and technology of superconducting materials. Turkish scientists are actively engaging in exploring novel superconducting materials, improving flux pinning mechanisms, and developing cost-effective production methods. These efforts align with global trends and aim to position Türkiye in the development and application of superconductivity. While the global market for superconductors is dominated by applications such as MRI systems — where over 5000 new units are installed annually worldwide — research in Türkiye focuses on innovative solutions to overcome technical and economic barriers, ensuring the country's competitiveness in this transformative field.

This study highlights the contributions of Turkish researchers in superconductivity over recent years, showcasing their efforts to tackle both fundamental and applied challenges in this dynamic area.

2. Research dynamics of last years

According to Web of Science (WoS) data, there has been substantial interest in superconductivity research. In Turkey, approximately 300 scientists and students have co-authored 3200 publications (with about 40000 citations on WoS and an H-index of 63) in SCI-indexed journals. Turkish researchers and research groups are now ranked among the leading contributors globally in the field of superconductivity.

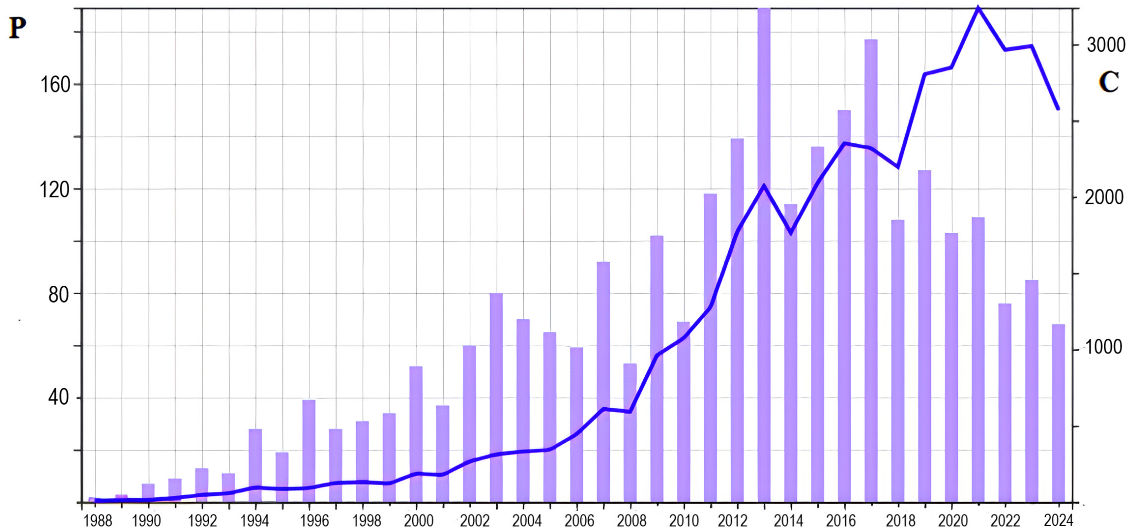

Fig. 1. Web of Sciences data on superconductivity for Turkey, P — number publications, C — number of citations (1988-2024).

The dynamics of publications and citations for the period 1988-2024 are presented in Figure 1. It is clear that there has been growing scientific activity related to the discovery of high-temperature superconductivity. In 2012, Ankara University Superconductivity Technologies Application and Research Centre (CESUR) was established, supported by the Ministry of Development (Project Dates: 2010-present) [http://cesur.ankara.edu.tr/] (Figure 2). The number of collaborating national universities is 11.

Fig. 2. SuperconductorTechnologies Application and Research Center (CESUR) in Ankara University.

3. Main turkish research on superconductivity

The primary research activities of Turkish scientists in the field of superconductivity encompass a wide range of innovative approaches aimed at advancing both the fundamental understanding and practical applications of superconducting materials.

One of the key areas of focus is material characterization, where researchers conduct in-depth studies to analyze the properties of superconducting materials, including their structural, electrical, and magnetic characteristics. This is critical for optimizing materials for various applications. Another significant area is the exploration of high-current and low-current applications, where Turkish scientists investigate how superconductors can be used in high-power devices such as magnetic energy storage systems, as well as in low-power technologies like sensitive sensors and circuits. The dynamics of Josephson junctions and superconducting digital electronics are also central to the research, as they have potential applications in quantum computing and high-speed digital systems. Additionally, Turkish scientists are developing both phenomenological and microscopic models of superconductivity to deepen the theoretical understanding of the phenomenon, which is essential for discovering new materials and improving existing technologies.

These diverse activities reflect the broad and interdisciplinary nature of superconductivity research in Türkiye, aimed at solving complex scientific and engineering challenges.

The following summarizes the significant findings of Turkish researchers in the field of superconductivity, focusing on material characterization, high-current applications, Josephson dynamics, and the development of phenomenological and microscopic models of superconductivity.

3.1 Material characterization measurements

Turkish researchers have made substantial contributions to the characterization of various Bi-based superconductors. The magnetic response of Bi-based superconductors of nominal composition against low ac field amplitudes is studied in terms of fundamental and third harmonic ac susceptibilities to investigate various physical parameters [1]. Harmonic ac susceptibilities, $\chi_n = \chi_{n'} + i\chi_{n''}$, and ac magnetization of a metallic granular superconductor of MgB_2 have been measured as a function of temperature, ac field amplitude and additional small dc field in the temperature range between 15 and 45 K in Ref [2]. The $Bi_2Sr_2Ca_2Cu_{3-x}Er_xO_{10+\delta}$ (x = 0.5 and 1.0) H–T_c system was prepared by glass–ceramic technique to investigate the microstructural formation, thermal and transport properties [3]. In addition, high-citation number studies such as those in Refs. [4–11] have contributed significantly to understanding the structural and physical characteristics of high-temperature superconductors.

3.2 High Current Applications

Turkish researchers have investigated various superconducting materials for high-current applications. AC loss measurements were conducted on mono-filament, 19-filament un-twisted, and 19-filament twisted MgB_2 superconducting wires (Figure 3), with magnetic fields applied perpendicular to the wire axis at different frequencies and temperatures ranging from 24 to 40 K. Additionally, AC losses were calculated using the critical state model for mono-filamentary Nb-sheathed MgB_2 wire under conditions matching the experiments. Among the samples, the twisted wire exhibited the lowest AC magnetization losses, approximately 10^{-5} J/m at 30 K [12] in an AC magnetic field with a 20 mT amplitude. This study is crucial for optimizing the performance of superconducting cables in practical applications.

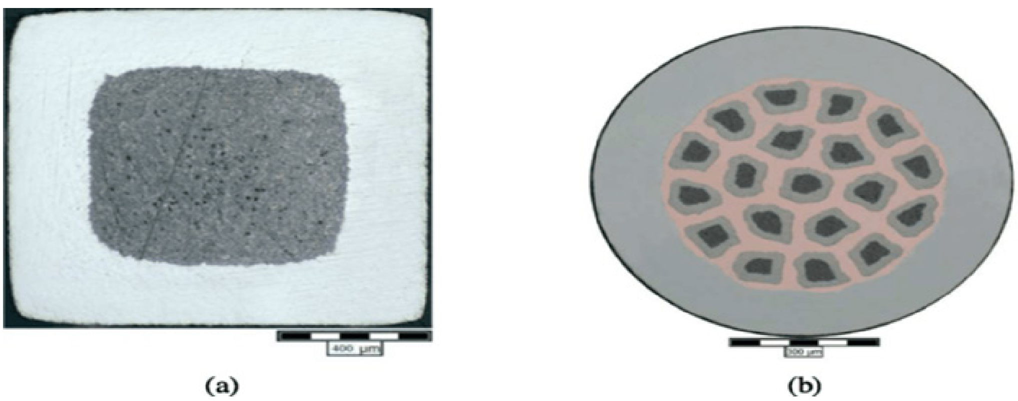

Fig. 3. Optical micrographs of the (a) S1 (mono-filamentary MgB_2 wire) and (b) S2 and S3 (multifilament MgB_2 wires) [12].

Further research focused on the development of a 6-kVA three-phase flux transfer-type current-limiting transformer [13]. In this design, the magnetic flux linked to the superconducting winding loops must remain constant. To achieve this, the magnetic flux is transferred via superconducting YBCO loops between two iron cores, enabling magnetic coupling between the primary and secondary coils. When the YBCO loops are in their superconducting state, 100% of the magnetic flux is transferred, allowing the device to function similarly to conventional transformers [13].

Very recently, a study [14] successfully produced a Fe-sheathed 6+1 multifilament wire using Cu/Nb/MgB_2 mono-core wires. The mono-filament wire was fabricated using a Mg + 2B powder mixture via the powder-in-tube method without any intermediate heat treatment. The powder mixture consisted of amorphous nano boron (PVZ Nano Boron, purity 98.5%, particle size < 250 nm) and high-purity Mg powder (PVZ Mg, purity 99%, particle size 74 μm). The multifilament wire was then produced using groove rolling and cold drawing techniques.

Additionally, a numerical study on the critical currents in nested superconducting MgB_2 coils was presented in [15]. In [16], numerical results were reported for a 50 kVA single-phase partially superconducting toroidal and core power transformer. These transformers were analyzed using COMSOL multiphysics software, incorporating AC/DC and heat transfer modules.

3.3 Low current application

References [17] and [18] experimentally demonstrated that rectangular mesa structures of intrinsic Josephson junctions in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) can serve as compact solid-state generators of continuous, coherent, and polarized terahertz (THz) radiation. These studies included measurements of the c-axis resistance as a function of temperature and current-voltage characteristics of THz-emitting mesas with lateral dimensions ranging from 30 × 300 μm^2 to 100 × 300 μm^2.

The fabrication of Josephson junctions based on $YBa_2Cu_3O_{7-\delta}$ (YBCO) was reported in [19] and [20]. Furthermore, the performance of DC-SQUIDs was evaluated with respect to the YBCO thin-film deposition rate in [21]. Additionally, the dependence of the phase and magnitude of the response of YBCO transition-edge bolometers on MgO substrates to near-infrared radiation, as influenced by the superconducting transition width, was investigated in [22] and [23].

3.4 Josephson Dynamics and Superconducting Digital Electronics

The book [24] explores new experimental investigations into the properties of Josephson junctions and systems, leveraging recent advancements in superconductivity. The theory of the Josephson effect is presented, incorporating the influence of multiband and anisotropy effects in novel superconducting materials. Moreover, The impact of anharmonicity in the current-phase relation on the dynamics of Josephson junctions is examined in detail [25-28].

Recent developments in analog and digital superconducting electronics are also discussed [29, 30], with particular emphasis on resistive single flux quantum (RSFQ) logic in digital electronics [31–33]. The application of Josephson junctions as superconducting quantum bits in quantum computing is analyzed, providing insights into their potential. Special attention is devoted to understanding the chaotic behavior of Josephson junctions and systems [34, 35].

Additionally, the implementation of a closed-cycle refrigerator test system, which remains in use today, is described. A 4-bit, 10 GHz analog-to-digital converter (ADC) is also presented, demonstrating the feasibility of the proposed ADC algorithm (Figure 4) [36].

3.5 Phenomenological and microscopic models of superconductivity

The book [37] explores the physical properties of unconventional superconductors, including cuprates, borocarbides, magnesium diboride, and oxypnictides. It provides a detailed analysis of anisotropy and multiband effects using Ginzburg-Landau and Eliashberg theories, offering insights into both theoretical and experimental implications. The application of the two-band Ginzburg-Landau theory to these superconducting compounds is discussed in Refs. [38–40]. Temperature dependencies of fundamental superconducting parameters are calculated, accounting for multiband effects (Figure 5) and anisotropy [41–42]. A comparison between theoretical predictions and experimental data is also provided. Additionally, analytical solutions to the microscopic Eliashberg and BCS theories are developed for two-band and anisotropic superconductors [43–45].

Ref. [46] demonstrates that the critical temperature for the Bose-Einstein condensation to normal phase transition of non-interacting bosons in cubic optical lattices has a linear dependence on the filling factor, particularly at high densities. The condensed fraction exhibits a linear power-law dependence on temperature, contrasting with ideal homogeneous Bose gases.

Numerical studies of $d_{x^2-y^2}$-wave pairing in the two-dimensional and two-leg Hubbard models are presented in [47, 48], based on results obtained from determinantal Quantum Monte Carlo and Density-Matrix Renormalization Group calculations.

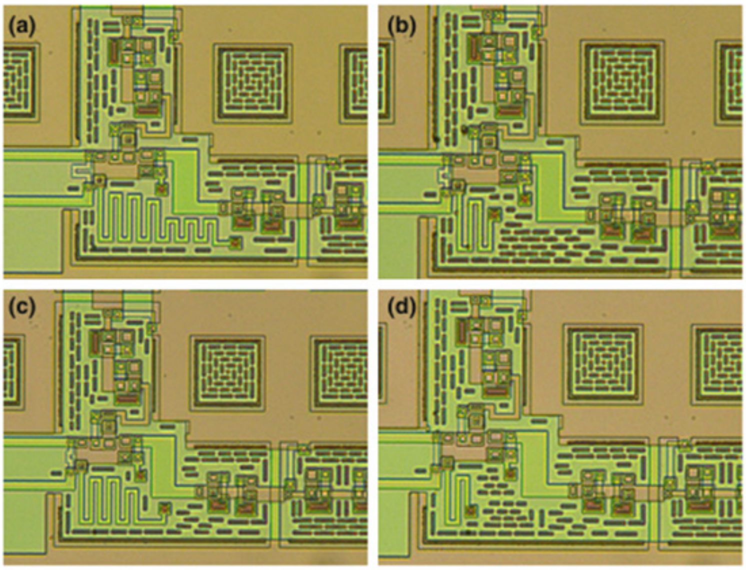

Fig. 4. Photographs of quasi-one junction comparator circuit's designs [see, 24].

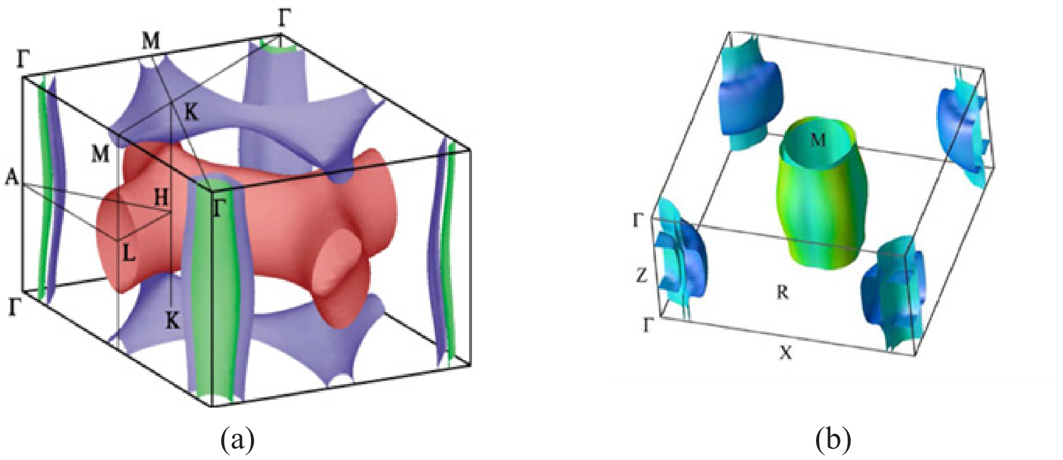

Fig. 5. Fermi surface of two-band compound (a) MgB_2 and (b) LaOFeP [37].

4. Conclusions

In conclusion, Turkish researchers have made significant contributions to the field of superconductivity, advancing both fundamental understanding and practical applications. Efforts are also focused on developing innovative models to address the complexities of superconductivity and overcome technical challenges. Türkiye's commitment to advancing this field is further demonstrated by the establishment of the Superconductivity Technologies Application and Research Centre (CESUR) and the growing collaboration among national universities.

Looking forward, while challenges such as material cost, scalability, and cooling requirements remain, the field is poised for continued growth. The focus will likely be on overcoming these barriers to enable more wide spread adoption of superconducting technologies, with an emphasis on real-world applications in energy, transportation, and quantum computing. We are grateful to our PhD student Ms. Fatima Al-Mokdad for her generous efforts in providing some of the paper contents, and help in coordination.

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