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Editorial

Focus on recent advances in superconducting films

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A convergence of ground-breaking projects has recently revitalized the field of superconductivity. Various initiatives such as compact fusion reactors, future high-energy physics experiments, and the thrilling prospects of quantum computing have given new impetus to research in this field. These advancements are fuelled by the remarkable properties of superconductors in the form of thin films. High temperature superconductors, and in particular $\mathit{RE}Ba_2Cu_3O_{7-\delta}$ (*RE*: rare-earth elements, *RE*BCO) films, enable the generation of ultra-high magnetic fields, while thin films of low temperature superconductors have found practical applications in Superconducting Radio Frequency (SRF) accelerating cavities and numerous electronic devices. Thin films, alongside single crystals, are also the preferred platforms for fundamental studies aimed at exploring and engineering the properties of superconducting materials. This Focus Issue provides a comprehensive overview of some of the most significant recent advances in superconducting films and offers insights into the evolving direction of the scientific community in this field.

According to the topics of the papers submitted to this Focus Issue, most of the effort is still devoted to *RE*BCO films with seven out of twelve papers about this topic. Since Coated Conductors rely on the quality of *RE*BCO films, there is a great interest in understanding the properties of this type of films to continue increasing the performances of the final products.

Three articles of this collection study pristine YBCO films but all of them with a different purpose. The authors used the chemical solution deposition (CSD) method to grow the films on three of the papers while pulsed laser deposition (PLD) was employed in the fourth one. Alcalà *et al* investigated the influence of growth temperature on the pinning-active defects in CSD-grown YBCO films [1]. By only tuning the growth temperature, and without introducing artificial pinning centres, the authors were able to tune the stacking fault formation and associated nanostrain resulting in different pinning scenarios. Films grown at an optimized temperature exhibited a remarkably larger amount of stacking faults that, in turn, facilitate the oxygen diffusion yielding overdoped films. The combination of both phenomena resulted in significantly higher critical current densities (J_c), up to 7 MA cm^{-2} at 77 K and self-field, for the optimized films in the whole range of temperatures and fields investigated. Another work that used CSD to prepare the films was the one of Daniel *et al* in which they added diethanolamine (DEA) to the YBCO precursor solution to explore its role as a chelating agent [2]. They investigated the interactions between DEA and a fluorine-free precursor solution,

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shedding light on the influence of DEA on the quality of the film growth and superconducting transport properties. They were able to grow YBCO films on single-crystal substrates with preferred *c*-axis orientation and remarkable self-field J_c at 77 K up to 4 MA cm^{-2}. The findings show that DEA has a positive effect on film growth and provide valuable information about the role of the chelating agents for the fabrication of high-quality YBCO films. The third article dealing with CSD-grown YBCO films is the one of Pop *et al* in which the authors focused on the difficult task of growing YBCO films on sapphire substrates [3]. The search of adequate substrates for every particular application is becoming more important since the experience with the use of certain devices brings new needs. In the case of the sapphire substrates, their use is particularly interesting due to their high thermal conductivity, making them attractive, in particular, for superconducting fault current limiters (SFCLs). Several factors that limit the quality of the films were identified, like the surface roughness of substrates, the reactivity between the buffer layers and YBCO, and the microcrack formation. After solving these different issues, the authors achieved YBCO films with attractive superconducting properties on this type of substrates. This research opens up new possibilities for enhancing the robustness of SFCLs against the harmful hot spots. Finally, the fourth article that reports results of pristine YBCO films is the one of Wahlberg *et al* in which the authors prepared untwinned 50 nm thick YBCO films by PLD on MgO substrates [4]. The authors studied the dependence of upper critical field with the doping of the films finding a strong decrease in the underdoped region of the phase diagram, similar to the one observed in relaxed single crystals. These results show the promising perspective of using thin films to investigate the phase diagram of high-T_c materials and also suggests the exploration of the strain-superconductivity relationship by varying film thickness.

The other three articles about *RE*BCO films introduced artificial pinning centres focusing on different aspects. On the one hand, Rijckaert *et al* followed the CSD *ex-situ* approach for the preparation of nanocomposite films and studied the effect of shape and crystallinity of the pre-formed nanocrystals on the pinning mechanism [5]. Two distinct nanoparticle synthesis methods led to HfO_2 nanoparticles with different shape and crystallinity. The formation and dimensions of the stacking faults are dissimilar on each case demonstrating not only the importance of controlling the size of the nanocrystals but also their structural properties and geometry to optimize the pinning properties. On the other hand, Hänisch *et al* compared the microstructural and transport properties of SmBCO films grown by CSD with and without $BaHfO_3$ nanoparticles [6]. Transport measurements in high magnetic fields revealed that, in the particular case of the SmBCO films, the additional $BaHfO_3$ nanoparticles had a positive effect on pinning only at low fields. The authors also found an interesting aging effect only observed in SmBCO films to date, where secondary phases are formed with time leading to an improvement critical current density. Finally, Wu *et al* introduced a novel approach to address the reduced pinning efficiency caused by the large lattice mismatch between $BaZrO_3$ (BZO) nanorods and YBCO in films grown by PLD [7]. The authors propose a dynamic lattice enlargement technique that induces *c*-axis elongation of the YBCO lattice near the BZO nanorods through Ca/Cu substitution. By reducing the lattice mismatch, a defect-free, coherent BZO/YBCO interface is achieved, leading to a remarkable five-fold enhancement of the critical current density at high magnetic fields and temperatures. This research not only highlights the critical role of coherent interfaces in maximizing pinning efficiency but also provides a practical and effective method to improve the performances of the YBCO films containing BZO nanorods.

Besides *RE*BCO compounds, other types of materials that are attracting the attention of the community in the last years are the Fe-based superconductors. These are also mainly being investigated in form of films since they are also discussed as good candidates for the preparation of Coated Conductors. In recent years, the research about this type of tapes has increased significantly, which is reflected in this collection with two papers about this topic. The first one was published by Holleis *et al* and focuses on the growth of Fe(Se,Te) films by PLD on RABiTS templates [8]. In this work, the authors demonstrated the successful growth of epitaxial Fe(Se,Te) films using a single yttrium oxide buffer layer and studied their magnetic granularity. The analysis of the local current distribution showed high local J_c values but also revealed the presence of granularity in the films, which is influenced by the out-of-plane orientation of the Ni-W substrate grains. This poses a challenge for the growth of such films on Ni-W substrates. Besides this work, Li *et al* analysed the magneto-transport properties of a series of (Li,Fe)OHFeSe films with different degrees of disorder prepared by modifying the growth conditions [9]. The authors observed a magnetic-field-enhanced shoulder-like feature in the resistive transition for films with weak disorder, indicating the presence of an emergent dissipative vortex phase. The study provides insights into the nature of the vortex states in unconventional high-temperature superconductors, here particularly highly anisotropic Fe-based superconductors, and opens up new possibilities for understanding and manipulating their behaviour.

The interest of the superconducting films is not restricted to *RE*BCO and Fe-based films and the potential use of the coated conductors, but extends to other areas. One of the papers in this collection is a good example. Arzeo *et al* report about the radio-frequency properties of niobium films deposited on copper substrates using high power impulse magnetron sputtering [10]. The authors demonstrate a significant reduction in radio-frequency losses, leading to lower surface resistance values compared to bulk niobium surfaces. These findings have important implications for the development of high-performance Nb/Cu coated accelerator cavities for the next-generation particle colliders.

Remarkably, superconducting films are still object of fundamental studies that yield new models and a deeper understanding of their material properties. In this collection, two papers are good examples of this type of basic research. On the one hand, Talantsev carried out a detailed study on atomically thin superconductors where he proposed a new approach for extracting the fundamental superconducting parameters of the films utilizing the upper critical field data [11]. By analysing the temperature dependence of the upper critical field, he deduced parameters such as the ground-state superconducting energy gap and the relative jump in electronic specific heat. The results obtained for different materials align well with the theoretical expectations for strongly and moderately strongly coupled electron-phonon-mediated superconductors. This approach offers a valuable tool for characterizing and understanding the properties of atomically thin superconducting systems. On the other hand, Chen *et al* investigated the growth conditions and the properties of niobium titanium nitride films sputtered on silicon substrate [12]. Despite the film being three-dimensional (3D), the authors observe a Berezinskii-Kosterlitz-Thouless-like transition, indicating the presence of hidden two-dimensional (2D) superconducting properties. This finding adds to the growing body of evidence supporting the existence of disorder-induced 3D to 2D superconductor transitions and calls for further theoretical investigations.

We hope this special issue will be the first of many on the same subject. There is still work to do in this area, and the search for higher critical current densities, larger pinning forces, and improved superconducting properties continues.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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