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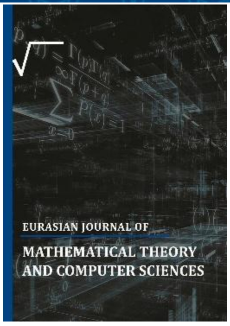

A COMPARATIVE REVIEW OF THE THICKNESS-DEPENDENT SUPERCONDUCTING PROPERTIES OF $YBA_2CU_3O_7-\Delta$ THIN FILMS

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ABSTRACT
This paper presents a comparative analysis of the thickness dependence of the superconducting transition temperature (TcT_cTc) in $YBa_2Cu_3O_7-\delta$ (YBCO) thin films based on previously published studies. The effects of film thickness, substrate type, and growth conditions on the superconducting properties are systematically reviewed. The comparison shows that TcT_cTc generally decreases as the film thickness is reduced to the nanoscale due to the combined influence of epitaxial strain, oxygen deficiency, finite-size effects, and surface/interface scattering. Differences observed among films grown on STO, LAO, LaO, and PrBCO-based heterostructures demonstrate the significant role of substrate-induced lattice mismatch and structural quality. The results indicate that optimizing film thickness together with substrate selection and oxygenation conditions is essential for achieving high superconducting performance. This review provides a comprehensive understanding of thickness-dependent superconductivity in YBCO thin films and highlights its importance for superconducting nanoelectronics, quantum devices, and high-field magnet applications.

Introduction

High-temperature superconductors (HTSs) are materials that exhibit zero electrical resistance at relatively high temperatures, typically close to the boiling point of liquid nitrogen, rather than at extremely low temperatures. Among these materials, $YBa_2Cu_3O_7-\delta$ (YBCO) is one of the most extensively studied and widely applied high-temperature superconductors. YBCO has a critical temperature ((T_c)) of approximately 92 K, allowing it to operate at liquid nitrogen temperature (77 K). This significantly reduces the need for expensive liquid helium cooling and lowers the operating costs of superconducting systems.

YBCO-based superconducting tapes are capable of generating extremely strong magnetic fields and are widely used in high-field magnet systems, scientific research facilities, particle accelerators, and medical diagnostic equipment. Moreover, YBCO maintains excellent superconducting performance even under strong magnetic fields, making it more attractive than conventional low-temperature superconductors for many practical applications.

In the field of quantum computing, superconducting materials play a crucial role in the fabrication of quantum bits (qubits). Although most current commercial quantum processors are based on aluminum or niobium, YBCO and other high-temperature superconductors have attracted increasing attention because they may enable operation at higher temperatures, reduce energy losses, and improve the stability of quantum devices. Consequently, YBCO is considered a promising candidate for future quantum technologies.

Among high-temperature superconductors, YBCO remains one of the most important functional materials due to its ability to operate at liquid nitrogen temperature, high critical current density, and excellent stability in strong magnetic fields. These outstanding properties have already led to its application in high-field magnets, highly sensitive superconducting sensors, power transmission systems, transportation technologies, and high-frequency electronics. Although YBCO is still mainly the subject of fundamental research in quantum computing, it is expected to play an increasingly important role in the development of next-generation superconducting quantum devices. These characteristics make YBCO one of the most promising functional materials for both current and future superconducting technologies.

The superconducting properties of YBCO thin films and heterostructures change significantly when their thickness is reduced to submicron and especially nanometer scales. These changes are primarily attributed to quantum size effects, surface and interface phenomena, variations in oxygen stoichiometry, and lattice deformation. As a result, important superconducting parameters, including the critical temperature ((T_c)), critical current density ((J_c)), and critical magnetic field, are considerably modified.

1. Superconductivity at the Nanoscale

As the thickness of YBCO films decreases, the motion of charge carriers becomes increasingly confined compared with that in bulk materials. When the film thickness becomes comparable to the superconducting coherence length ((\xi)) and the London penetration depth ((\lambda)), superconductivity gradually exhibits two-dimensional (2D) characteristics.

Under these conditions:

- quantum fluctuations become stronger;
- vortex dynamics are significantly modified;
- phase coherence is weakened;
- superconductivity becomes more susceptible to suppression.

Consequently, superconductivity in ultrathin YBCO films is much more sensitive to structural imperfections than in bulk crystals.

2. Suppression of the Critical Temperature with Decreasing Film Thickness

Numerous experimental studies have demonstrated that the superconducting transition temperature decreases as the thickness of YBCO thin films is reduced. This phenomenon can be explained by several physical mechanisms:

- Surface and interface scattering: Cooper pairs experience stronger scattering at surfaces, interfaces, and structural imperfections.
- Oxygen deficiency: The superconducting properties of YBCO are highly sensitive to oxygen content. Oxygen loss occurs more readily in ultrathin films, reducing the carrier concentration.
- Lattice strain: Mismatch between the lattice parameters of the substrate and the YBCO film generates internal strain that alters the crystal structure.
- Increased defect density: Higher concentrations of dislocations and grain boundaries hinder the movement of Cooper pairs.

As a consequence:

- thick YBCO films generally exhibit (T_c) values of approximately 90–92 K;
- (T_c) gradually decreases as the thickness is reduced to several tens of nanometers;
- superconductivity may disappear completely when the film thickness approaches only a few nanometers.

Overall, reducing the thickness of YBCO thin films and heterostructures to submicron and nanoscale dimensions significantly alters their superconducting properties. The suppression of the critical temperature is mainly associated with enhanced surface and interface scattering, oxygen non-stoichiometry, lattice deformation, and stronger quantum fluctuations. In addition, anomalous variations of (T_c) have been reported within certain thickness ranges, which are believed to originate from interface physics, charge transfer, and two-dimensional quantum effects. Understanding these phenomena is of great scientific and technological importance for the development of superconducting nanoelectronics, quantum devices, and highly sensitive superconducting sensors.

Numerous experimental and theoretical studies on YBCO thin films have demonstrated that the reduction of the superconducting transition temperature ((T_c)) with decreasing film thickness cannot be explained by a single mechanism. Instead, it results from the combined influence of several physical factors. The most widely accepted explanations reported in the literature are summarized below.

1. Strain Effect

YBCO thin films are commonly grown epitaxially on crystalline substrates such as $SrTiO_3$ (STO), $LaAlO_3$ (LAO), and MgO. Because the lattice parameters of YBCO differ from those of the substrate, epitaxial strain is generated during film growth.

This strain leads to several structural and electronic modifications, including:

- changes in Cu–O bond lengths;
- variations in the spacing between CuO_2 planes;
- modifications of charge-carrier density and pairing energy;
- partial distortion of crystal symmetry.

When the film thickness is very small, the epitaxial strain is strongest, leading to a noticeable reduction in the superconducting transition temperature.

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As the film thickness increases, strain gradually relaxes, allowing (T_c) to approach its bulk value.

Overall, previous investigations indicate that the thickness dependence of (T_c) in YBCO thin films arises from the combined effects of epitaxial strain, oxygen non-stoichiometry, surface and interface scattering, finite-size effects, and structural defects, rather than from a single dominant mechanism.

Comparative Analysis of Previous Studies

The dependence of the superconducting transition temperature (TcT_cTc) on the thickness of $YBa_2Cu_3O_7{-}\delta$ (YBCO) thin films has been extensively investigated using different deposition techniques, substrates, and growth conditions. Despite differences in experimental procedures, all studies consistently demonstrate that the superconducting properties of YBCO are strongly influenced by film thickness. However, the rate of TcT_cTc suppression and the critical thickness at which superconductivity deteriorates differ considerably among the reported investigations.

The work of H.Y. Zhai and W.K. Chu investigated the influence of interfacial strain on YBCO thin films deposited on LaO and $SrTiO_3$ (STO) substrates. Their results show that extremely thin films exhibit significantly reduced superconducting transition temperatures. For films grown on LaO, TcT_cTc increases from approximately 64.9 K at a thickness of 2.87 nm to approximately 91.3 K at 163.8 nm. A similar trend is observed for films deposited on STO, where TcT_cTc increases from about 66.8 K at 3.68 nm to approximately 91.3 K at 162.9 nm. These results indicate that increasing film thickness gradually relaxes the interfacial strain and allows the superconducting properties to approach those of bulk YBCO.

The study entitled "Thickness Dependence of Superconductivity for $YBa_2Cu_3O_\gamma$ Ultra-Thin Films" focuses on ultrathin YBCO films grown on STO substrates. In contrast to thicker films, the superconducting transition temperature remains substantially lower throughout the investigated thickness range. At approximately 2 nm, the measured TcT_cTc is only about 25 K, whereas increasing the thickness to nearly 25 nm raises TcT_cTc to about 88.4 K. These observations clearly demonstrate that superconductivity is strongly suppressed in films whose thickness approaches only a few crystallographic unit cells.

A different behavior was reported in the study "Suppression of Superconductivity at the Nanoscale in Chemical Solution Derived $YBa_2Cu_3O_7{-}x$ Thin Films with Defective $Y_2Ba_4Cu_8O_{16}$ Intergrowths." For YBCO films prepared on $LaAlO_3$ (LAO) substrates, the superconducting transition temperature increases from approximately 56.4 K at a thickness of 19.6 nm to nearly 84.7 K at 242 nm. Although TcT_cTc increases with thickness, the maximum value remains noticeably lower than the bulk value reported in other investigations. This suggests that, besides thickness, structural defects and oxygen non-stoichiometry may substantially influence the superconducting properties.

The fourth study, "Thickness Dependence of the Superconducting Transition Temperature of YBCO," investigated films incorporating PrBCO layers. The reported data reveal a pronounced increase in TcT_cTc with increasing thickness. Very thin films exhibit superconducting transition temperatures below 25 K, while thicker films exceeding 500 nm reach approximately 86 K. Compared with the previous studies, superconductivity develops more gradually, indicating that the buffer layer and interface characteristics significantly affect superconducting behavior.

A comparison of these investigations demonstrates a common trend: the superconducting transition temperature generally increases with increasing film thickness, regardless of substrate material or deposition approach. Nevertheless, the absolute TcT_cTc values differ considerably between studies. Films grown on STO and LaO substrates recover bulk-like superconductivity at relatively smaller thicknesses, whereas chemically derived films and PrBCO-based heterostructures exhibit lower transition temperatures over a broader thickness range. These differences indicate that thickness alone cannot fully explain the superconducting behavior of YBCO thin films.

Discussion

The comparative analysis of the published studies demonstrates that the superconducting transition temperature (TcT_cTc) of $YBa_2Cu_3O_7{-}\delta$ (YBCO) thin films is strongly influenced by film thickness, substrate material, and the structural quality of the deposited layer. Although all investigated studies report a general increase in TcT_cTc with increasing film thickness, the magnitude of this increase differs considerably. These differences indicate that several physical mechanisms simultaneously influence superconductivity in ultrathin YBCO films.

Effect of Interfacial Strain

One of the primary mechanisms responsible for the thickness dependence of TcT_cTc is epitaxial strain caused by lattice mismatch between the substrate and the YBCO film. During the initial stages of thin-film growth, the crystal lattice of YBCO adapts to the substrate lattice, producing elastic deformation within the CuO_2 planes. This deformation modifies the Cu–O bond lengths and Cu–O–Cu bond angles, both of which are essential for superconducting charge transport.

The data reported by H.Y. Zhai and W.K. Chu clearly illustrate this phenomenon. Both LaO- and STO-based films exhibit relatively low TcT_cTc values at thicknesses below approximately 5 nm, whereas the transition temperature gradually approaches the bulk value as the film thickness increases beyond 100 nm. This behavior suggests that epitaxial strain is strongest in ultrathin films and progressively relaxes as additional layers are deposited. Consequently, thicker films exhibit improved crystallinity and enhanced superconducting properties.

The comparison between LaO and STO substrates also indicates that the choice of substrate slightly affects the recovery rate of superconductivity. Although both substrates eventually produce transition temperatures close to 91 K, the STO-grown films maintain slightly higher TcT_cTc values throughout most of the investigated thickness range. This observation suggests that STO provides more favorable lattice matching and lower residual strain than LaO under the reported experimental conditions.

The comparison also suggests that several physical mechanisms act simultaneously. Interfacial strain is dominant in ultrathin epitaxial films, oxygen deficiency becomes increasingly important during nanoscale growth, while structural defects and interface quality determine how rapidly superconductivity recovers as film thickness increases. Therefore, the superconducting transition temperature should be regarded as a result of the combined influence of thickness, substrate-induced strain, oxygen stoichiometry, and crystalline quality rather than thickness alone.

Conclusion

This comparative review demonstrates that the superconducting transition temperature (TcT_cTc) of $YBa_2Cu_3O_7-\delta$ (YBCO) thin films strongly depends on film thickness. The analyzed studies consistently show that TcT_cTc decreases in ultrathin films and gradually approaches the bulk value as the thickness increases.

The reduction of TcT_cTc is mainly attributed to the combined effects of interfacial strain, oxygen deficiency, finite-size effects, and substrate-induced structural changes. In particular, STO and LaO substrates generally provide better superconducting performance than LAO and PrBCO-based structures under the reported conditions.

These findings indicate that optimizing film thickness, substrate selection, and oxygenation conditions is essential for improving the performance of YBCO-based superconducting devices. The results of this review provide useful guidance for the development of superconducting nanoelectronics, quantum devices, SQUID sensors, and other high-temperature superconducting applications.

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