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ANISOTROPIC MICROSTRAIN AND ITS RELATIONSHIP WITH THE OUT-OF-PLANE TEXTURE AND THE SUPERCONDUCTING PROPERTIES OF YBCO FILMS GROWN ONTO SrTiO_3 (100) AND LaAlO_3 (100) SUBSTRATES BY CHEMICAL SOLUTION DEPOSITION

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Abstract. The anisotropic microstrain and its relationship with the out-of-plane texture and superconducting properties of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) films grown onto SrTiO_3 (100) and LaAlO_3 (100) single-crystal substrates by the chemical solution deposition sol-gel technique are considered. X-ray diffraction analysis present (00l) reflections from the YBCO phase in both films, with c-axis grain fraction values of 88% and 81% for the SrTiO_3 and LaAlO_3 , respectively. The ω -scan measurements around the (005) reflection reveal a multi-layer structure for both films: three sub-layers with $\Delta\omega = 0.35^\circ$, 0.83° and 1.0° for YBCO/ SrTiO_3 , and two sub-layers with $\Delta\omega = 0.45^\circ$ and 2.0° for YBCO/ LaAlO_3 . Microstructural analysis using Debye-Scherrer and Williamson-Hall methods indicates that the YBCO films exhibit significant anisotropic microstrain, with the strain state being more homogeneous on LaAlO_3 than on SrTiO_3 . The superconducting properties show a strong dependence on microstrain: The YBCO film on LaAlO_3 exhibit a higher onset critical temperature ($T_{C(\text{onset})} \approx 92$ K) compared to that grown onto SrTiO_3 ($T_{C(\text{onset})} \approx 78$ K), despite the latter having a higher degree of c-axis texture. This work demonstrates that anisotropic microstrain plays a dominant role in determining the superconducting properties of YBCO films grown by the chemical solution deposition technique, highlighting that structural texture alone is not the only factor governing superconducting performance.

Keywords: superconductivity, anisotropic microstrain, out-of-plane texture, sol-gel, chemical solution deposition.

1. Introduction

The discovery of high-temperature superconductors (HTS) in complex oxides such as the cuprates has enormously increased the interest in growing epitaxial thin films of a wide range of transition metal oxides displaying remarkable functional properties [1, 2]. Among these materials, $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) has emerged as one of the most promising candidates for technological applications due to its ability to transport high critical current densities at the boiling point of liquid nitrogen (77 K). However, the strongly anisotropic nature of

YBCO, characterized by a short coherence length and a large anisotropy in their physical properties, imposes requirements on the films microstructure to achieve optimal superconducting performance. From this, the anisotropy is an intrinsic factor that dictates the magnetic properties of YBCO, thus having a great impact for many applications [3]. The anisotropy of YBCO makes it necessary to use epitaxial layers with biaxial texture, i.e., with good out-of-plane and in-plane orientation, to achieve critical current densities ($J_c(B, T)$) higher than 10^6 A/cm² at 77 K [3, 4]. In thin films, texture refers to the relative ordering of crystallites to a particular direction of growth, called the texture axis [4, 5]. Out-of-plane texture, which refers to the orientation of the crystallographic axes with respect to the substrate normal, is particularly crucial due determines the alignment of the superconducting CuO₂ planes. A high uniaxial texture, where the grains grow with their *c*-axis perpendicular to the substrate, is essential for maximizing current transport [6]. Contrariwise, the presence of *a*-axis oriented grains or the formation of 90° grain boundaries can strongly deteriorate the critical currents and therefore the potential applications [7]. Quantifying the degree of texture in YBCO layers is commonly achieved by various experimental techniques, such as X-ray diffraction (XRD), pole figure analysis, ω -scans (rocking curves), Raman spectroscopy and electron microscopy [8].

Chemical solution deposition (CSD), and in particular the sol-gel method, has emerged as a low-cost and highly scalable alternative for the fabrication of YBCO superconducting films [9, 10]. Unlike vacuum deposition techniques, CSD does not require expensive equipment and offers precise control over stoichiometry and microstructure [11]. Among the advantages of the fluorine-free sol-gel method are the stability of the precursor solution, a denser film microstructure, and the elimination of HF formation during processing [12, 13]. The combination of sol-gel chemistry with deposition techniques such as ink-jet printing offers significant advantages, including reduced waste of the precursor solution, production in long lengths, and the possibility of switching from depositing a coating to a multifilamentary superconductor [14]. This makes the CSD route an attractive option for the industrial production of coated conductors [15]. Moreover, these solution processes provide better homogeneity and composition control than other techniques like sputtering or MOCVD, and can render easiness of coating on substrates with various shapes and forms by simple techniques such as dip coating.

Despite the advances in the growth of YBCO films, there is a gap in the quantitative understanding of how out-of-plane texture, microstrain, and anisotropic microstrain together influence the superconducting properties. Most studies have focused on texture characterization, but few have systematically addressed how structural inhomogeneities, such as the microstrain generated during growth, affect the superconducting properties [10, 16]. The microstrain in the crystallites can affect the width of the diffraction peaks and is therefore a crucial parameter that must be considered in an accurate microstructural analysis [17]. Furthermore, the stress between the substrate and the YBCO lattice significantly affects the in-plane and out-of-plane orientations, as well as the growth parameter window [18]. Understanding this relationship is essential for optimizing growth conditions and maximizing superconducting performance. In particular, the correlation between uniaxial texture and anisotropic microstrain has been scarcely explored, despite its importance for confirming the high ordering of the CuO₂ superconducting planes [3, 6].

From this, the aim of the present work is to investigate the anisotropic microstrain and its relationship with the out-of-plane texture and the superconducting properties of YBCO films grown on SrTiO₃ (100) and LaAlO₃ (100) single-crystal substrates by the chemical solution deposition (CSD) sol-gel technique. The out-of-plane texture was analysed by X-ray diffraction technique, where rocking curves (ω -scans) around the (005) reflection provide information about the degree of inclination of the *c*-axes of the superconducting grains with respect to the growth direction. The microstrain and crystallite size were evaluated using both the Debye-Scherrer and Williamson-Hall methods to separate the contributions of crystallite size and lattice strain to the peak broadening, enabling a detailed analysis of the microstrain anisotropy. The superconducting properties were correlated with the out-of-plane texture parameters ($\Delta\omega$) and the microstrain (ϵ).

2. Experimental Methodology

The superconducting YBCO films were prepared by a chemical solution deposition (CSD) followed by thermal treatments, according to the procedure reported elsewhere [10, 20]. In brief, for a solution containing 1.5 g of YBCO 1.3487gr of Cu acetate (Cu (OOCCH₃)₂•H₂O), 0.7613 g of Y acetate (Y (OOCCH₃)₃•4H₂O) and 1.1502 g of Ba acetate (Ba (OOCCH₃)₂) were reacted. The acetates were mixed and completely dissolved in a solution of ethanol (C₂H₅OH) and oxalic acid (H₂C₂O₄) (ratio 1:1). Subsequently, the solution left to decant 12 h in a matrix of oxalic acid and ethanol alcohol, subjected to a magnetic stirrer at 250 rpm to ensure a correct

homogeneity in the mixture. The resulting product is a precursor solution comprising of oxalates of Y, Ba and Cu in a colloidal matrix of oxalic acid. These oxalates were then deposited onto substrates of strontium titanate (SrTiO₃) (100) and lanthanum aluminate (LaAlO₃) (100) by using a Fisher pipette. The sample was immediately dried at 40 °C in order to remove volatile elements. This process was repeated 7 times.

The crystallization and epitaxial growth of the YBCO layer was achieved by *ex situ* heat treatments, as represented in Fig. 1. The film was heated and sintered at 860 °C in a tubular furnace (LENTON LTF-PTF Model 16/610) in oxygen atmosphere for 12h, and subsequently re-oxygenated at 600 °C. The furnace was programmed to anneal and to quench the sample at the same ratio (1 °C/min).

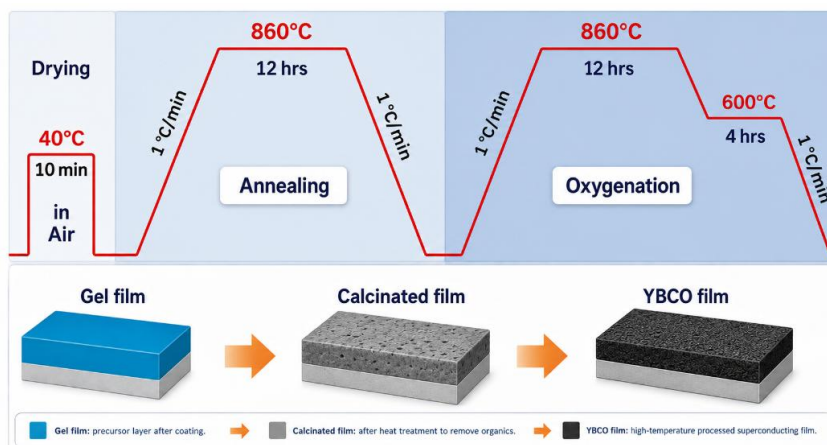


Fig.1. Schematic representation for the *ex-situ* heat treatments performed on CSD YBCO films on LaAlO₃ and SrTiO₃ substrates. The slow heating rate (1 °C/min) released volatile hydrocarbons. The YBCO superconducting films are obtained after oxygenating the samples at 860 °C.

The crystallization of the sample was studied by X-ray diffraction (XRD). The data were collected from 8° to 80° (0.04° step) using a powder universal diffractometer Bruker D8 with Cu K_α1 radiation ($\lambda = 1.54056$ Å). The texture analysis was achieved by Rocking Curves measurements around the reflection (005) $2\theta = 38.72^\circ$ with 0.02° (ω) step and time step 6 seconds by 15° to 23° intervals. The surface morphology of the film was inspected using a NIKON ME600L optical microscope. Magnetic measurements were performed using a Quantum Design DC-MPMS-SQUID magnetometer equipped with a 7 T superconducting magnet. The superconducting transition temperature T_c was determined from temperature-dependent measurements of the magnetization $M(T)$ under $H_{ext} = 100$ and 500 Oe.

3. Results and discussion

Figure 2 shows the surface morphology of the YBCO films on SrTiO₃ and LaAlO₃ substrates obtained by the oxalate CSD route and after oxygenation at 860 °C. The results reveal that the samples consist on granular films where the YBCO grains are uniformly dispersed over the substrates surface and forming small groups.

Figure 3 shows the XRD patterns of the annealed YBCO films on SrTiO₃ and LaAlO₃ substrates obtained by CSD. The presence of the peaks (003), (004), (005), (006) and (007) reveal epitaxial growth in the c-direction or texture axis. The strong reflections (black in colour) (100), (200) and (300) correspond to the SrTiO₃ and LaAlO₃ substrates. The Y₂BaCuO₅ (Y211), CuO and Y₂O₃ are also detected as secondary phases. The Y211 phase (PDF card 78-1719 [3]) is detected by the reflections around 25.92° , 30.40° , 40.96° and 61.52° . The CuO phase might be present due to inhomogeneities in the starting precursor solution [3]. This phase is observed in relative minor amount with reflections around 27.72° (just observed on YBCO/STO sample) and 35.56° . Whereas, the Y₂O₃ reflections are around 58.32° and 68.08° .

The out-of-plane texture of the formed films was analysed from the fraction of c-axis orientation, f_s , by using Eq. (1):

$$\frac{I^{005}}{I^{200}} = \frac{f_c \cdot I_{stand}^{005}}{(1 - f_c) I_{stand}^{200}} \quad (1)$$

where, I_{stand} is the standard intensity obtained for randomly oriented samples (PDF card 40-159 [3]).

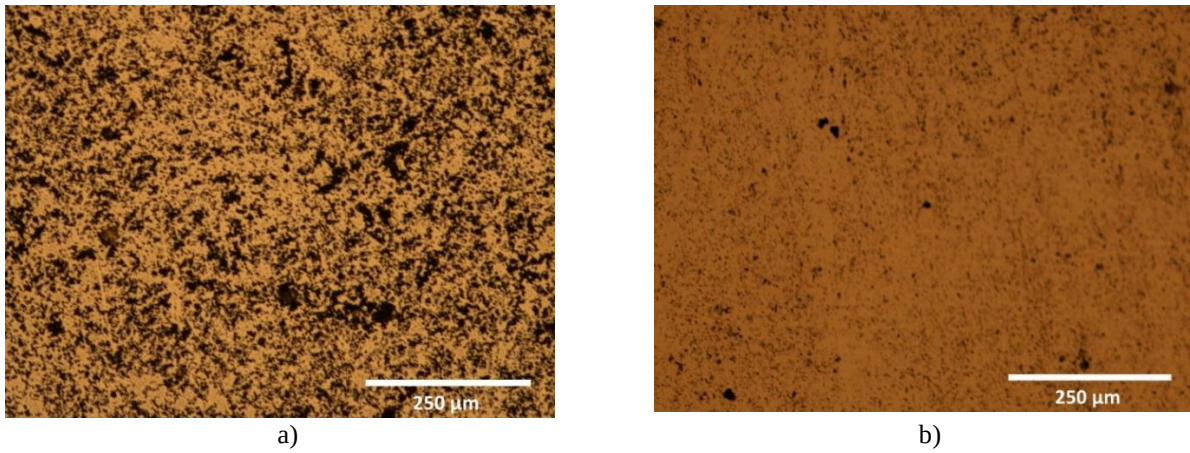


Fig.2. Optical microscope images of the YBCO film on (a) SrTiO₃ and (b) LaAlO₃ substrate, obtained by CSD and annealing. The images are 5× magnified.

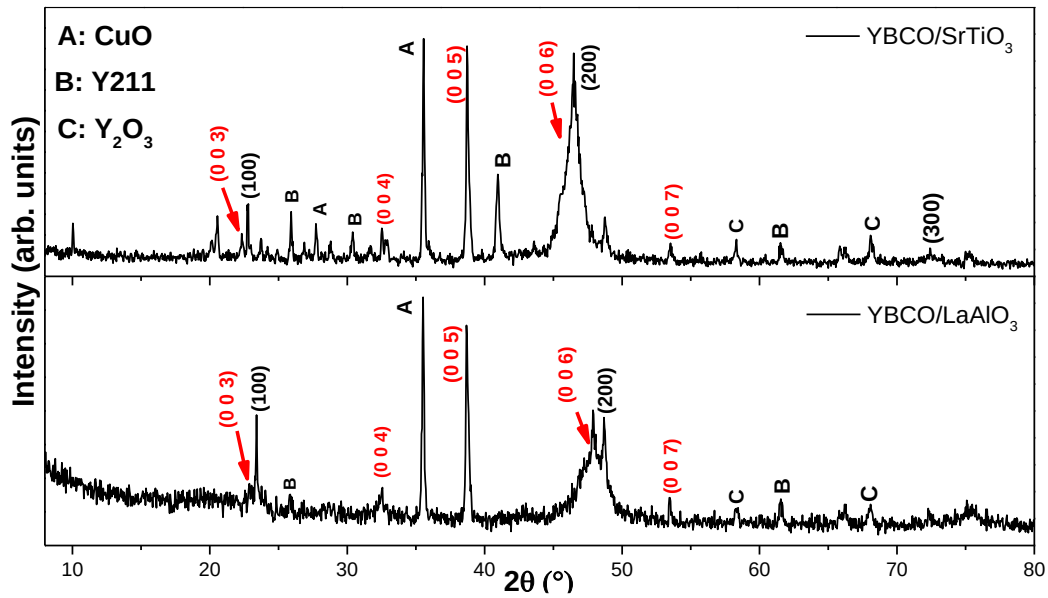


Fig.3. XRD pattern of an annealed YBCO film on SrTiO₃ (top) and LaAlO₃ (bottom) substrate obtained by CSD.

We obtain $f_s = 0.88$ and 0.81 for the YBCO onto SrTiO₃ and LaAlO₃ substrates, respectively. Therefore, 88% of the superconductor phase in the YBCO on SrTiO₃ and 81% on LaAlO₃ followed the preferential orientation given by the substrate. These values have been achieved since the lattice constant of both substrates are quite similar to that of YBCO orthorhombic. Thus, a higher percentage of out-of-plane textured grains better are obtained for YBCO on SrTiO₃ than on LaAlO₃.

3.1 Microstructural Analysis: Crystallite Size and Microstrain.

To evaluate the microstructural parameters, a first approximation of the crystallite size D was obtained using the Debye-Scherrer equation [3, 21], neglecting peak broadening caused by residual stress:

$$D = \frac{K\lambda}{\beta_{\text{corr}} \cos \theta_{\text{hkl}}} \quad (2)$$

Here, D is the average crystallite size (hereinafter D_{Scherrer}), λ is the wavelength of the applied X-ray, θ_{hkl} is the Bragg's angle, β_{corr} is the instrumentally corrected full width at half maximum (FWHM) in radians, and $K = 0.916$ is the Scherrer constant [21]. The obtained D_{Scherrer} values are summarized in Table 1.

However, microstrain within the crystallites also contributes to peak broadening [22], requiring a more accurate analysis. From this, the Williamson Hall method was used to simultaneously determine the lattice strain (ϵ) and the crystallite size (in following D_{WH}) using the equation [22]:

$$\beta_{\text{corr}} \cos \theta = \frac{K\lambda}{D_{WH}} + 4\epsilon \sin \theta \quad (3)$$

The lattice strain (ϵ) was obtained from the slope of the linear fit of $\beta_{hkl} \cos \theta$ vs $4 \sin \theta$ plots for the main diffraction peaks, while the intercept $K\lambda/D_{WH}$ yields the volume-weighted crystallite size (D_{WH}). The WH data are listed in Table 1, while Williamson-Hall plots and microstructural parameters obtained results are summarized in Figure 4.

Table 1. Main diffraction peaks and both Debye-Scherrer and Williamson Hall analysis data.

Sample	Phase	(hkl)	2 θ (°)	θ (°)	β_{obs}	β_{obs} (rad)	β_{inst} (rad)	β_{sample} (rad)	$\beta \cos \theta$ (rad)	4sin θ	D_{scherrer} (nm)	$\bar{D}_{\text{scherrer}}$ (nm)
YB CO/ STO	YBCO	(004)	30.40	15.20	0.22	0.003839	0.002094	0.00322	0.00311	1.048	48.0	47.2
		(005)	38.72	19.36	0.20	0.003491	0.002268	0.00266	0.00251	1.327	58.1	
		(006)	46.60	23.30	0.28	0.004887	0.002443	0.00423	0.00388	1.582	36.6	
		(007)	53.52	26.76	0.25	0.004363	0.002792	0.00335	0.00299	1.799	46.2	
	Y211	(102)	25.92	12.96	0.16	0.002792	0.002094	0.00185	0.00180	0.896	83.6	55.5
		(112)	30.40	15.20	0.16	0.002792	0.002094	0.00185	0.00179	1.048	83.6	
		(321)	40.96	20.48	0.32	0.005585	0.002443	0.00502	0.00470	1.400	30.8	
		(330)	61.52	30.76	0.40	0.006981	0.002792	0.00640	0.00550	2.048	24.2	
	CuO	(110)	27.72	13.86	0.16	0.002792	0.002094	0.00185	0.00180	0.958	83.6	110.8
		(002)	35.56	17.78	0.145	0.002531	0.002268	0.00112	0.00107	1.221	138	
	Y ₂ O ₃	(440)	58.32	29.16	0.36	0.006283	0.002792	0.00563	0.00492	1.946	27.5	27.8
		(622)	68.12	34.06	0.36	0.006283	0.002967	0.00554	0.00459	2.242	28.0	
YB CO/ LA O	YBCO	(004)	30.48	15.24	0.24	0.004188	0.002094	0.00363	0.00350	1.051	42.6	43.2
		(005)	38.74	19.37	0.22	0.003839	0.002268	0.00309	0.00292	1.328	50.0	
		(006)	46.60	23.30	0.28	0.004887	0.002443	0.00423	0.00388	1.582	36.6	
		(007)	53.48	26.74	0.26	0.004538	0.002792	0.00357	0.00319	1.798	43.4	
	Y211	(102)	25.80	12.90	0.16	0.002792	0.002094	0.00185	0.00180	0.892	83.6	45.1
		(330)	58.44	29.22	0.36	0.006283	0.002792	0.00563	0.00492	1.950	27.5	
		(303)	61.56	30.78	0.40	0.006981	0.002792	0.00640	0.00550	2.049	24.2	
	Y ₂ O ₃	(622)	68.08	34.04	0.36	0.006283	0.002967	0.00554	0.00459	2.241	28.0	28.0

The Debye-Scherrer crystallite sizes (D_{scherrer}) for the YBCO phase in the films on SrTiO₃ and LaAlO₃ are 47.2 nm and 43.2 nm, respectively (Table 1). This difference, although modest, indicates that the YBCO grains are slightly larger on the SrTiO₃ substrate. This is somewhat surprising given that LaAlO₃ has the smaller lattice mismatch magnitude (-0.83%) compared to SrTiO₃ (+1.35%). The larger crystallite size on STO may therefore be attributed to other factors beyond the lattice mismatch, such as differences in surface energy, interfacial chemistry, and nucleation kinetics between the two substrates. For the Y211 secondary phase, the average D_{scherrer} values are 55.5 nm (STO) and 45.1 nm (LAO), while CuO (only in STO) shows a larger size of ~111 nm and Y₂O₃ exhibits the smallest and most consistent size (~28 nm) on both substrates.

The Williamson-Hall analysis, which separates the contributions of crystallite size and microstrain, yields significantly larger crystallite sizes (D_{WH}) for YBCO: 85.2 nm (STO) and 81.0 nm (LAO), estimated from the intercept. This discrepancy between D_{scherrer} and D_{WH} is attributed to the presence of microstrain, which contributes to the peak broadening and is accounted for in the WH method. The microstrain values (ϵ) obtained from the slopes of the WH plots are 0.0275% for YBCO on STO and slightly lower for LAO (~0.025%), while the Y211 phase exhibits similar strain values (~0.0275%). Notably, the lower strain in the YBCO phase on LAO, despite its poorer texture, suggests that the strain is not the main factor limiting the out-of-plane texture; rather, the lattice mismatch and the substrate-film interface quality play a more critical role.

A crucial aspect of this analysis is the anisotropic nature of the microstrain. The orthorhombic structure of YBCO gives rise to different strain contributions along the crystallographic axes, which are not captured by the uniform deformation model (UDM) commonly used in WH analysis. Additionally, the oriented growth of the YBCO phase promotes the appearance of anisotropic microstrain. The linearity of the WH fits, as indicated by the R^2 values, is reasonable for the secondary phase Y211 (0.776 and 0.991 for STO and LAO, respectively) but poor for YBCO (0.059 for STO and 0.0004 for LAO). This poor linearity for YBCO is a direct consequence of the anisotropic microstrain present in the orthorhombic lattice, where the strain is not isotropic but rather distributed differently along the a-, b- and c-axes.

In contrast, the no-oriented growth structure of Y211 (orthorhombic) allows a better linear fit, indicating that the strain in this secondary phase is more isotropic and well described by the UDM. The low R^2 for YBCO also reflects the fact that the peak broadening in this phase is not purely dominated by size and strain effects, but also by the presence of structural defects and the strong texture, which introduce additional strain anisotropy. The good agreement between the D_{Scherrer} and D_{WH} for the Y211 phase (55.5 nm and 81.4 nm on STO; 45.1 nm and 77.8 nm on LAO) suggests that the strain contribution in this secondary phase is relatively uniform and well described by the UDM. The larger WH size indicates that the crystallites are less strained than the YBCO matrix, which is consistent with their formation as isolated precipitates during the thermal treatment [23].

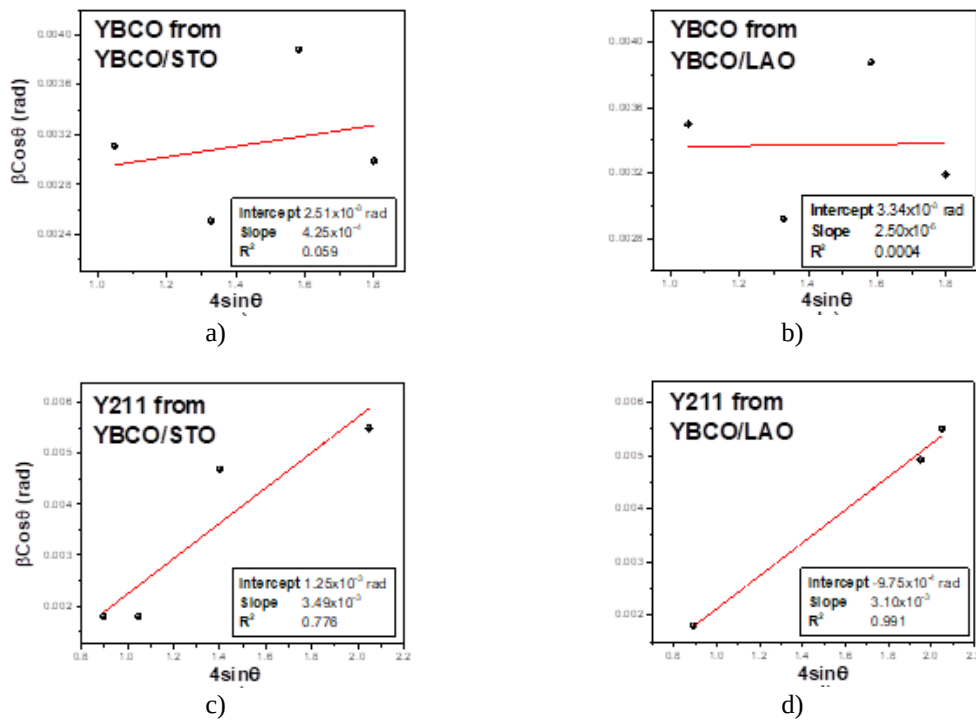


Fig.4. Williamson Hall plots of YBCO phase from a) YBCO/STO and b) YBCO/LAO samples; W-H plots from Y211 phase from and c) Y211/STO and d) Y211/LAO samples.

The anisotropic microstrain analysis reveals that the YBCO films on both substrates exhibit significant strain heterogeneity, which directly influences the superconducting properties. The STO substrate, with a larger lattice mismatch (+1.35%), induces a higher tensile strain in the YBCO lattice compared to the LAO substrate (-0.83%). This higher strain on STO leads to a higher density of structural defects and oxygen disorder, which ultimately affects the superconducting transition temperature (T_C). Conversely, the lower strain on LAO favours an optimal oxygen ordering and a higher hole doping level in the CuO_2 planes, thereby promoting a higher T_C despite the lower degree of c-axis texture ($f_s = 0.81$ for LAO vs 0.88 for STO). This highlights that the anisotropic microstrain, rather than the out-of-plane texture alone, plays a dominant role in determining the superconducting properties of these films.

3.2 Out-of-plane texture: Rocking curves

The out-of-plane texture was analysed by rocking curves XRD around the (005) reflection. This reflection was chosen because its intensity is higher than the other (00l) reflections and also because its position in XRD plot (around $2\theta = 38.72^\circ$) is far away from any other reflection from the substrate (in particular the (200) reflection). The Figure 5 shows the results for the two films and the $\Delta\omega$ values are listed in Table 2. The FWHM (full width half maximum) value of the Rocking curve provides relevant information about the degree of inclination of the c-axes of the superconducting grains with respect to the normal of the plane substrate.

Each Gaussian function provides different $\Delta\omega$ values meaning that the films consist on multilayers of YBCO of different texture [7]. Since the texture of the films is strongly influenced by the substrate, the smaller $\Delta\omega$ values in each sample should correspond to layers close to the YBCO/substrate interface, whereas high $\Delta\omega$ values represent textures of layers close to the surface of the film.

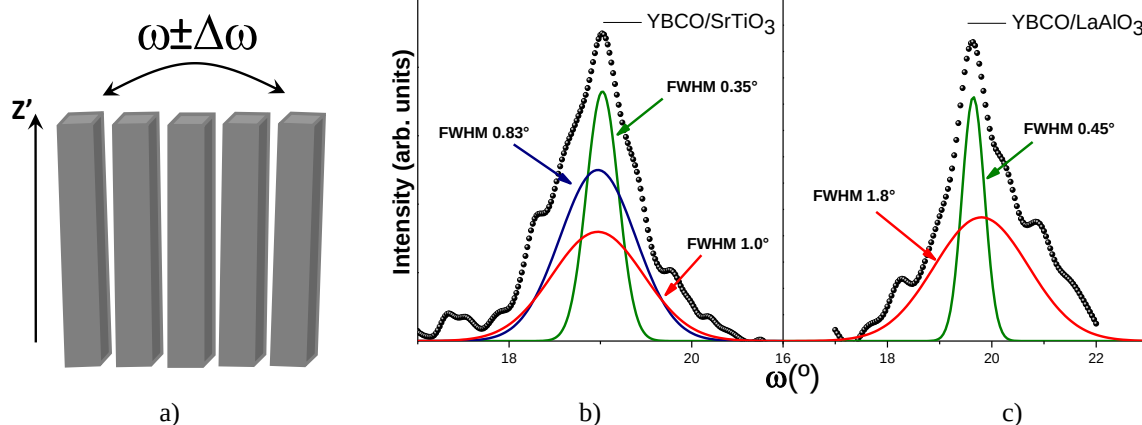


Fig.5. (a) The rocking curve is a measure of the degree of inclination in the grains with respect to the normal of the substrate (z'). (b) Rocking curves measurements corresponding to the (005) reflection for YBCO/STO. Is observed the presence of three textured groups of YBCO crystallites with different inclination angles values ($\Delta\omega$); (c) RC measurement of the YBCO/LaAlO₃ sample where two textured layers groups are observed.

Table 2. f_s values and Full width at the half maximums (FWHM, $\Delta\omega$) of the rocking curves corresponding to the reflection (005) for YBCO films obtained by the oxalate CSD route on SrTiO₃ and LaAlO₃ substrates and after oxygenation at 860 °C.

	Lattice constant mismatch (Δa)	f_s	$\Delta\omega$
YBCO/STO	+1.35	0.88	0.35° (Close to the film/ substrate interface)
			0.83° (Intermediate YBCO crystallites group)
			1.0° (Close to the surface)
YBCO/LAO	-0.83	0.81	0.45° (Close to the film/ substrate interface)
			2.0° (Close to the surface)

Note that the sample deposited on LaAlO₃ presents only two layers with different texture although the inner layer presents the poorest texture (with $\Delta\omega = 0.45^\circ$) compared to those from the other samples. Despite the YBCO film deposited on SrTiO₃ contains three layers with different texture, the texture of its inner layer is the best ($\Delta\omega = 0.35^\circ$).

3.3 Superconducting properties: Correlation with Texture and Microstrain

The temperature dependence of the magnetic moment (Fig. 6) reveals a marked difference in the superconducting properties of the YBCO films on SrTiO₃ and LaAlO₃. The sample grown on LAO exhibits a sharp diamagnetic transition with an onset critical temperature $T_{C(\text{Onset})} \approx 92$ K, while the film on STO shows a significantly lower $T_{C(\text{Onset})} \approx 78$ K. This notable difference is attributed to the combined effect of out-of-plane texture and anisotropic microstrain. The LAO substrate, with a smaller lattice mismatch (-0.83%), induces a lower strain state in the YBCO lattice, resulting in a more homogeneous distribution of strain and a lower density of structural defects. This lower strain favours an optimal oxygen ordering and a higher hole doping level in the CuO₂ planes, thereby promoting a higher T_C . On the other hand, the relative larger tensile strain imposed by the STO substrate (+1.35%) introduces a higher density of structural defects and oxygen disorder, which effectively suppresses T_C to 78 K. Interestingly, although the STO substrate yields a higher degree of c-axis texture ($f_s = 0.88$) compared with the LAO ($f_s = 0.81$) and a slightly larger crystallite size (47.2 nm and 43.2 nm for STO and LAO, respectively), the final T_C is more strongly influenced by the anisotropic microstrain and the resulting oxygen stoichiometry than by the purely structural texture. This finding highlights the critical role of microstrain anisotropy in determining the superconducting performance of YBCO films. A distinctive feature observed in the ZFC curve of the YBCO/STO sample is a clear increase in the magnetic moment below 15 K, indicating a paramagnetic contribution that superimposes on the diamagnetic signal. This low-temperature paramagnetic tail is not observed in the YBCO/LAO sample, suggesting a higher concentration of magnetic secondary phases in the YBCO/STO film. As confirmed by the XRD analysis (Fig. 3 and Table 1), the YBCO/STO sample exhibits a larger relative abundance of CuO and Y211 phases. Both of these secondary phases contain magnetic Cu²⁺ ions: CuO is antiferromagnetic below 230 K but retains a net paramagnetic or weak ferromagnetic moment at very low temperatures, while Y211 is known to exhibit antiferromagnetic correlations that can give rise to a Curie-type paramagnetic response.

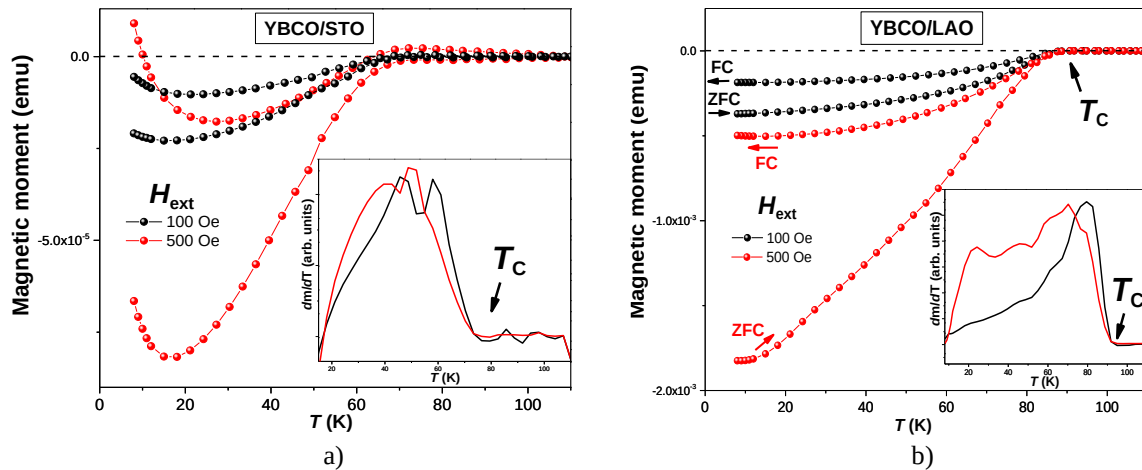


Fig.6. Temperature dependence of the magnetic moment for YBCO films grown on (a) STO and (b) LAO substrates, measured under $H_{\text{ext}} = 100$ and 500 Oe (ZFC and FC modes). The insets show the first derivative of the ZFC curves, highlighting the onset critical temperature.

The presence of these magnetic contributions, particularly at temperatures below 15 K, competes with the Meissner shielding, reducing the effective diamagnetic moment and making the ZFC branch less negative. This effect also complicates the precise determination of the lower critical field and the shielding fraction for the STO sample.

4. Conclusion

The anisotropic microstrain and its relationship with the out-of-plane texture and the superconducting properties of YBCO films grown by chemical solution deposition onto SrTiO_3 and LaAlO_3 substrates were investigated. The structural and textural analysis revealed that both films exhibit epitaxial growth in the c -direction, with a higher fraction of c -axis oriented grains on SrTiO_3 (88%) compared to LaAlO_3 (81%). The ω -scans further demonstrated that the films are composed of multiple sub-layers with distinct out-of-plane textures, indicating a complex growth mode influenced by the substrate. The YBCO/STO film exhibited three textured sub-layers with $\Delta\omega$ values of 0.35° , 0.83° , and 1.0° , while the YBCO/LAO film showed two sub-layers with $\Delta\omega = 0.45^\circ$ and 2.0° . This multilayer structure reflects the evolution of the texture from the substrate interface to the film surface, where the best texture is achieved near the interface. A crucial finding emerged from the microstructural analysis using both Debye-Scherrer and Williamson-Hall methods, which revealed the presence of significant anisotropic microstrain in the YBCO films. The poor linearity of the Williamson-Hall fits for the YBCO phase ($R^2 = 0.059$ for STO and 0.0004 for LAO), in contrast to the excellent linearity for the secondary Y211 phase ($R^2 = 0.776$ for STO and 0.991 for LAO), is a direct consequence of the anisotropic strain distribution in the orthorhombic YBCO lattice. This indicates that the strain is not isotropic but varies along the crystallographic axes, which is a critical factor influencing the properties of the film. The microstrain values obtained were 0.0275% for YBCO on STO and slightly lower ($\sim 0.025\%$) for LAO, with the Y211 phase exhibiting similar strain values ($\sim 0.0275\%$). The lower strain on LAO, despite its poorer texture, suggests that the lattice mismatch and substrate-film interface quality play a more critical role in determining the strain state than the out-of-plane texture alone.

The superconducting properties were found to be strongly correlated with the anisotropic microstrain rather than with the out-of-plane texture alone. The YBCO film on LAO, despite having a lower degree of c -axis texture ($f_s = 0.81$), exhibited a significantly higher onset critical temperature ($T_{C(\text{Onset})} \approx 92$ K) compared to the film on STO ($T_{C(\text{Onset})} \approx 78$ K). This is attributed to the lower lattice mismatch of LAO (-0.83%) inducing a more homogeneous strain distribution and a lower density of structural defects, which favor optimal oxygen ordering and hole doping in the CuO_2 planes. Conversely, the larger tensile strain imposed by the STO substrate ($+1.35\%$) introduces a higher density of structural defects and oxygen disorder, effectively suppressing T_C . Additionally, the presence of a paramagnetic upturn at low temperatures in the YBCO/STO sample, attributed to magnetic secondary phases (CuO and Y211), further confirms the higher degree of structural and chemical inhomogeneity in this film. This study shows that anisotropic microstrain is a crucial

parameter that governs the superconducting performance of CSD-derived YBCO films. While achieving a high degree of out-of-plane texture is important, minimizing anisotropic microstrain through appropriate substrate selection or strain engineering is essential for optimizing the superconducting properties.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRedit author statement

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Statement on the use of Artificial Intelligence.

The authors declare that no artificial intelligence tools were used to generate scientific content, results, or conclusions of this article.

Data Availability Statement

The data are available upon reasonable request from the authors.

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