(305) $SrTiO_3$ as substrate for coherently tilted epitaxial $YBa_2Cu_3O_x$ thin films

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High T_c superconducting $YBa_2Cu_3O_x$ (YBCO) thin films have been prepared on (305) $SrTiO_3$ (STO) substrates. X-ray diffraction analysis and Rutherford backscattering experiments reveal that the *c*-axis of the layers is directed along the [001] STO axis. Bragg reflection measurements from YBCO lattice planes with high *h*, *k*, and *l* indices confirm that the film growth is epitaxial and almost single domain. For the critical current density j_c(77 K) values of 2×10^6 and 1×10^3 A/cm^2 have been found in the [010] and [50$\bar{1}$] YBCO directions, respectively.

The question of the superconducting properties anisotropy in the case of the high T_c superconductors (HTS) is of great importance now. Recent experiments show strong anisotropy in coherence length ξ,[1] critical current density j_c and resistivity ρ above the critical transition temperature T_c[4] between the directions parallel and perpendicular to the CuO_2 planes in the $YBa_2Cu_3O_x$ (YBCO). The origin of such behavior may be in the quasi-two-dimensional nature of high T_c superconductivity.[5]

Measurements of the anisotropy of the transport properties on YBCO single crystals are difficult because of the well pronounced layered nature that inhibits the preparation of monocrystalline structures with dimensions in the *c*-direction large enough for j_c measurements. Requirements of YBCO thin films are also exceptionally high. One should use epitaxial films which are single domain, properly oriented and free from twins.

The aim of this work is to study the possibility of the growth of coherently tilted epitaxial YBCO thin films on specially oriented (305) $SrTiO_3$ (STO) substrates and apply these for the study of the anisotropy in the YBCO transport properties. Jia *et al.* showed that YBCO can cover steps on the (001) STO substrates. If the angle α between the normal to the (macroscopic) step surface and the (001) STO direction is below $\approx 40°$, the YBCO on the step is *c*-axis oriented.[6] The surface of our (305) STO substrates is similar to that of a step with $\alpha = 30.96°$. Therefore, we expect YBCO to grow on (305) STO substrates with the *c*-axis tilted with an angle of 31° relative to the substrate surface normal, and directed along the [001] STO axis, see Fig. 1. If epitaxial and single domain films can be made, they allow us to study the anisotropy in the electrical properties of YBCO thin films for the first time, then also anisotropic behavior of many other physical properties of YBCO can be studied on these films.

We have studied single and double layers of YBCO and $PrBa_2Cu_3O_x$ (PBCO), grown on (305) STO (Akzo International Research SCT) using off-axis rf magnetron sputtering as a deposition technique. The deposition setup and typical sputter parameters are described elsewhere.[7]

X-ray diffraction analysis (XRD) and 2 MeV $^4He^+$ Rutherford backscattering spectrometry (RBS) were used to determine the orientation of the (double) layers. The XRD experiments were performed on a Philips Materials Research Diffractometer (MRD) equipped with parallel beam x-ray optics.[8] The RBS data were analyzed using the RUMP computer code.[9]

Superconducting properties have been derived from the critical temperature $T_{c,zero}$, resistivity ρ, and critical current density j_c measurements. We have prepared YBCO strips with different angles φ between the direction of the strip and the [010] STO axis. They enable us to study the anisotropy in j_c in our coherently tilted YBCO films. For $\varphi = 0°$, the measuring current can flow along the *a-b* planes of the YBCO along the [010] direction and the critical current density $j_{c,\parallel}$, parallel to the CuO_2 planes, can be determined. For $\varphi = 90°$, the current is forced to flow along the [50$\bar{1}$] direction of the YBCO. The critical current density measured along this direction will be near $j_{c,\perp}$, the critical current density perpendicular to the CuO_2 planes.

The MRD is designed to allow one- or two-dimensional scanning of any region of reciprocal space. A $2\theta/\omega$ scan directed along the STO *c*-axis, the STO [001] direction in Fig. 1, revealed strong (0 0 10), (0 0 11), and (0 0 13) peaks from the superconductor (see Fig. 2). The (009) and (0 0 12) reflections from the YBCO coincided with the (003) and (004) reflections of the STO, respectively. These results confirm that the *c*-axis of the YBCO is tilted over 31° when referred to the surface normal and parallel to the [001] STO direction.

To investigate the single-crystal nature of the YBCO film, reciprocal space maps of a series of Bragg reflections with high *h*, *k*, and *l* indices have been measured.[8] Figure 3 shows a map of the (038)-(308) pair of Bragg reflections. The measured difference in 2θ angle of 1.34° corresponds exactly to the calculated value. The relative intensities of the (038) and (308) peaks indicate that the film is almost single domain with the *b*-axis of the YBCO lying in the (305) STO surface plane (see Fig. 1). The full width at half maximum (FWHM) of the rocking curve of the

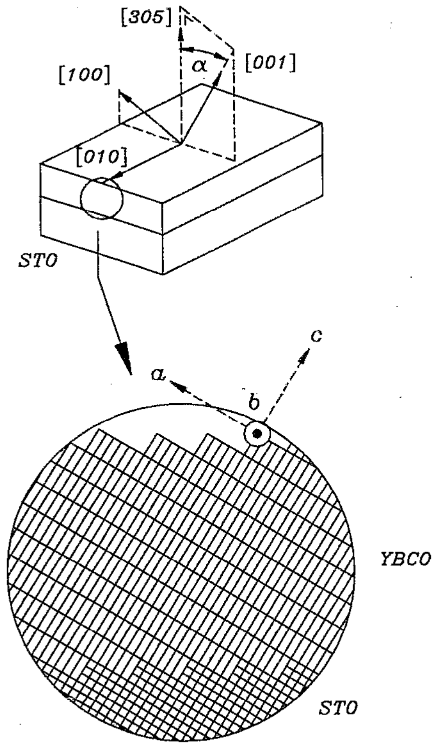

FIG. 1. Schematic, idealized view of a coherently tilted epitaxial YBCO thin film on a (305) STO substrate. The c-axis of the YBCO is tilted over $\alpha \approx 31°$ when referred to the (macroscopic) surface normal.

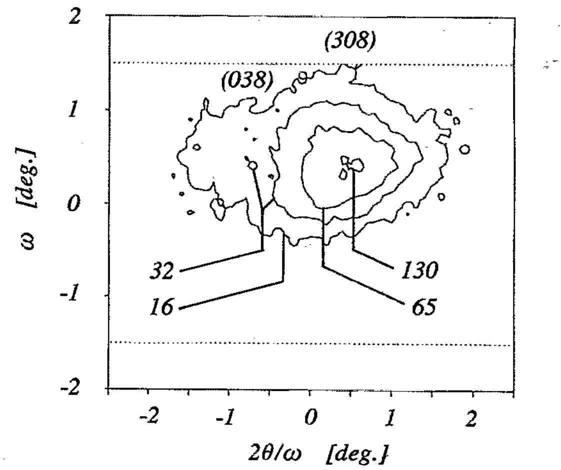

FIG. 3. Measurements of the (038)-(308) Bragg reflections pair of the YBCO film on a (305) STO/YBCO sample. Intensities of the different levels are indicated.

(308) Bragg reflection is less then 1°, as can be seen in Fig. 3. A map of the (025)-(205) pair of reflections gave similar results. The present x-ray diffraction studies indicate that the film is almost entirely single domain.

We have performed resistivity measurements on two sets of 5 YBCO strips with $\varphi = 0°$, 22.5°, 45°, 67.5°, and 90° as a function of temperature T. The strips have a length of 200 and 100 μm and their widths equal 40 and 10 μm, respectively. The YBCO film thickness is 74 nm. All the strips with a width of 40 μm showed a $T_{c,\text{zero}}$ of 88 K. The $T_{c,\text{zero}}$ of the strips with a width of 10 μm decreased from 88 to 84 K upon increasing φ. However, $T_{c,\text{onset}}$ remained unchanged. In Fig. 4, ρ measured at 100 K on the YBCO strips with different φ is shown. We see a strong anisotropy in ρ(100 K), comparable to the results of Penney *et al.*[4] Also the resistivity ratio $\rho(300)/\rho(100)$ (RRR) depends on the width w of the YBCO strip and on φ, see Table I.

We also have measured j_c at 77 K on the two sets of YBCO strips with different w and orientation φ. In these measurements we used a criterion of 0.01 mV/cm. A very strong anisotropy can be observed (see Fig. 4). We have found values of 2×10^6 and 1×10^3 A/cm^2 for j_c(77 K) in the [010] and [50$\bar{1}$] YBCO directions, respectively. Our results indicate a much larger anisotropy in j_c than results of Dinger *et al.*[2] and Crabtree *et al.*[3]

Application in microelectronics requires that YBCO can be used in multilayers, e.g., in combination with PBCO. In Fig. 5, results of RBS experiments on a (305) STO/YBCO/PBCO sample are given. A random spectrum

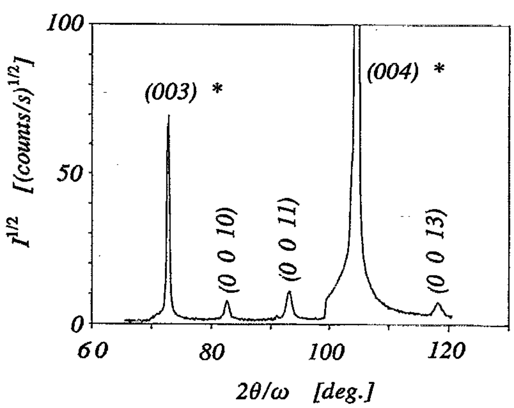

FIG. 2. $2\theta/\omega$ XRD scan along the STO c-axis, confirming that the c-axis of the YBCO is tilted over 31° when referred to the surface normal and parallel to the [001] STO direction. STO substrate peaks are labeled with "*". Reflections from the YBCO are labeled with their corresponding indices. Note that the root of the x-ray intensity I has been plotted as a function of $2\theta/\omega$.

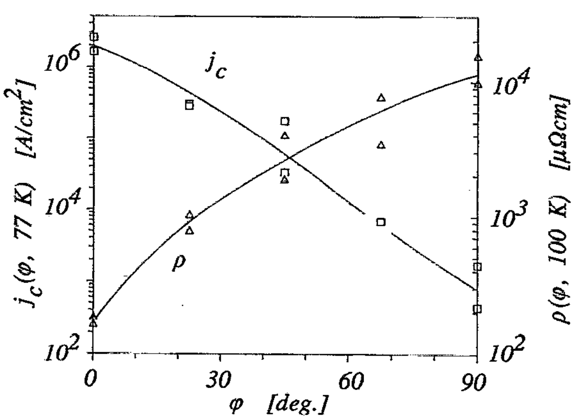

FIG. 4. Critical current density j_c at 77 bK and resistivity ρ at 100 K measured on two sets of 5 YBCO strips on (305) STO as a function of the angle φ between the direction of the strip and the [010] STO direction. j_c measurements are indicated by □, the ρ measurements by Δ. The solid lines are guides to the eye.

TABLE I. RRR(w,φ) as a function of the width w and the orientation φ of an YBCO strip on (305) STO.

φ[deg.]	0	22.5	45	67.5	90
RRR(40 μm,φ)	2.40	1.57	1.33	1.31	1.28
RRR(10 μm,φ)	2.28	1.24	1.13	1.01	0.56

and a channeling spectrum, taken with the HE ion beam aligned with the [001] axis of the (305) STO substrate, are shown. For the YBCO bottom layer, a minimum backscattered yield χ_{min} of about $\approx 30\%$ is found. For the top PBCO layer, χ_{min} is only 6%. These low χ_{min} values indicate that the YBCO/PBCO double layer is well oriented, especially the PBCO top layer. In simulating the RBS spectrum in Fig. 5, we found for the YBCO and PBCO layer thicknesses values of 60 and 100 nm, respectively. No significant interface reactions can be observed.

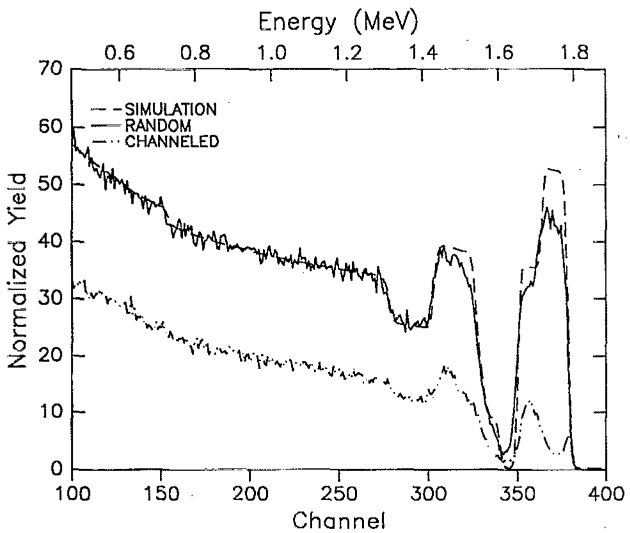

FIG. 5. RBS experiments on a (305) STO/YBCO/PBCO sample. The sample was mounted with a tilt of 31° in the channeling experiments, so the He ion beam was parallel to the [001] STO direction.

As a conclusion, epitaxial high T_c superconducting single and double layers of YBCO and PBCO have been prepared on (305) STO substrates. X-ray diffraction analysis and Rutherford backscattering experiments reveal that the c-axis of the layers is directed along the [001] axis of the STO. Bragg reflection measurements from YBCO lattice planes with high h, k, and l indices confirm that the film growth is epitaxial, and almost single domain. About 90% of the YBCO thin film has its b-axis parallel to the (305) STO surface, whereas the remaining part of the film has the a-axis parallel to this direction. For the critical current density j_c (77 K) values of 2×10^6 and 1×10^3 A/cm^2 have been found in the [010] and [50$\bar{1}$] directions of the YBCO, respectively.

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