Single-phase superconducting $Bi_2Sr_2Ca_1Cu_2O_y$ films on $(Y,Nd)AlO_3$ substrates

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Single-phase superconducting $Bi_2Sr_2Ca_1Cu_2O_y$ films have been grown on a single-crystal $(Y,Nd)AlO_3$ substrate. The films have a well-defined **c** texture and are highly oriented in the (**a**,**b**) plane.

1. Since the discovery of high-T_c superconductivity,[1,2] a substantial effort has been devoted to growing high-quality films of high-T_c oxide superconductors. Films of the Bi system with a **c** orientation have been grown by several methods: laser deposition and magnetron sputtering[3,4]and molecular beam epitaxy.[5] The materials used most commonly as substrates have a cubic lattice: $SrTiO_3$, MgO, yttrium-stabilized zirconium (ZrO_2 with 9% Y_2O_3), and rhombohedral sapphire (Al_2O_3 with a ZrO_2 buffer sublayer).

Promising for microwave applications are substrates of $LaAlO_3$. This crystal has a distorted cubic lattice which matches ideally with the lattice constants of the basal plane of the 1-2-3 superconductors. The difference between lattice constants **a** and **b** of this crystal can be exploited to orient films in the basal plane. In the correct orientation, the critical current j_c should be high. The prospects for raising the j_c's are particularly good for films of the Bi system, for which the resistance transition has a sharp onset at temperatures above 100 K but then has a resistance tail amounting to a fraction of a $\mu\Omega \cdot$ cm down to 40–50 K. The absence of a critical current at these temperatures gives rise to an electromagnetic noise, even in the highest-quality BSCCO films. The reason for the low j_c's is the presence of crystalline intergrowths of phases of the $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ homologous series[6] and interfaces between disoriented crystallites.

2. In order to grow BSCCO films oriented in the basal plane, we selected as substrate yttrium monoaluminate, $YAlO_3$, which is a perovskite-like crystal of orthorhombic symmetry with space group $D_{2h}^{16}(Pbnm)$. Its lattice constants are[1)] $a=0.512$, $b=0.533$, $c=0.737$ nm. Doped with rare-earth elements, this crystal is used as active medium for near-IR solid state lasers. Doping does not alter the symmetry of the crystal; it just leads to some insignificant changes in the lattice constants. Because of the structural features of yttrium aluminate, its thermal stability, its chemical inertness, and the approximate matching of the lattice constants in the (001) plane

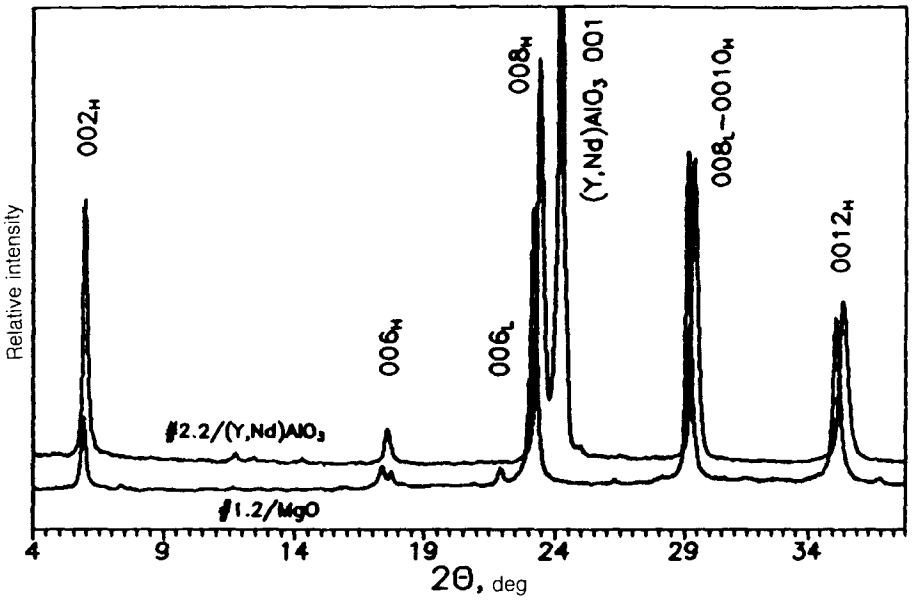

FIG. 1. Diffraction patterns of single-phase film 2.2, grown on an (Y,Nd)AlO_3 substrate (upper curve), and of two-phase film 1.2, grown on MgO (lower curve). The subscript L means that the reflection belongs to the 2201 low-temperature phase, and H means the 2212 high-temperature phase.

with the constant **a** in the tetragonal lattice of the $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ compounds, this crystal holds promise as a substrate material for the epitaxial growth of BSCCO films. The low loss tangent, $\tan\delta = 1\times10^{-3}$ (10 MHz, 300 K), the low dielectric constant $\epsilon = 16$, and the thermal expansion coefficients $k_a = 5.1\times10^{-6}$ K^{-1}, $k_b = 4.2\times10^{-6}$ K^{-1}, $k_c = 11.7\times10^{-6}$ K^{-1}, which are close to those of BSCCO, add to the attractiveness of these substrates.

We are aware of only one report[7] of the growth of a $Bi_2Sr_2Cu_1O_y$ (2201) film on this substrate by molecular beam epitaxy. In the present letter we are reporting data on the synthesis of single-phase **c**-texture $Bi_2Sr_2Ca_1Cu_2O_y$ films, oriented in the (**a**,**b**) plane, on the new substrate (Y,Nd)AlO_3.

3. *The (Y,Nd)AlO_3 substrates* were prepared by starting with high-purity yttrium monoaluminate and neodymium oxide (the N_2dO_3 dopant was added in a concentration of 1–3% by mass). After an annealing at 1000 °C and a homogenization, the mixture, pressed into pellets, was annealed in air for 15–20 h at 1200°C. Single crystals of Nd:$YAlO_3$ were grown from the melt by the Czochralski method on a computer-controlled Galaxie apparatus. The crystals grew in the [010] direction on an oriented twin-free seed. The as-grown crystals were annealed for 24 h at 1400°C. The mechanical treatment of the substrates included cutting, grinding, and chemical-mechanical polishing to remove the damaged layer and to produce an epitaxial-class surface.

The surface was monitored by electron diffraction. The roughness, measured with

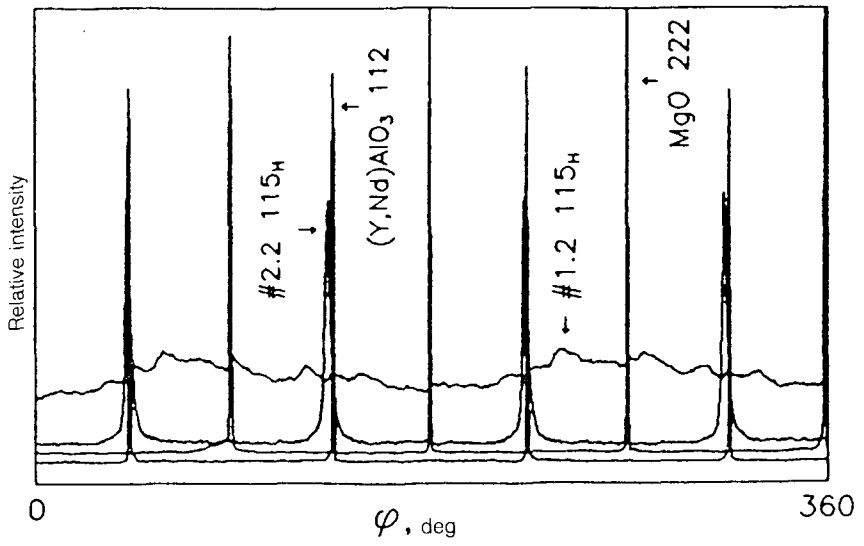

FIG. 2. φ scans of nontextural peaks, 112 [the (Y,Nd)AlO_3 substrate] and 222 (the MgO substrate), and also of the 115 reflection of the 2212 phase, for films 1.2 and 2.2. The high-quality single-crystal structure of the substrates, the pronounced **a** orientation of the film on the (Y,Nd)AlO_3 substrate, and the complete disorientation in the (**a**,**b**) plane of the crystallites on the MgO substrate are all evident.

a profilometer, did not exceed $R_z = 10$ Å . The substrates were 10×15 mm^2 in area and had a thickness of 0.5 mm. Their lattice constants were $a=0.517\ 88$, $b=0.532\ 77$, $c=0.736\ 90$ nm. The deviation from the (001) orientation did not exceed 20′.

Thin films of the 2212 composition were grown by *dc magnetron sputtering* of a ceramic target in an Ar^+ atmosphere. The $Bi_2Pb_{0.5}Sr_2Ca_2Cu_3O_y$ target was prepared by solid-phase synthesis from the oxides of Bi, Pb, and Cu and the carbonates of Sr and Ca. The doping with lead was carried out by a step-by-step procedure during the synthesis.[8] The lead oxide (in an amount of 0.17 of a formula unit) was added three times, after each 30-h annealing and regrinding of the pellet. The total duration of the annealing in air at 835°C was 150 h. According to x-ray results, the target consisted of the 2223 phase (60%) and the 2212 phase (40%).

The films were grown on a VUP-5M apparatus. The film deposition time was 1/2 h (the corresponding thickness was 1200 Å). The substrate temperature did not exceed 80°C during the deposition. The distance from the substrate to the target was 5 cm. After the deposition, the x-ray-amorphous films were subjected to *annealing in air* at 820–870°C for 0.5–1.5 h. For comparison of the results, we simultaneously deposited and annealed films on a substrate of natural MgO (001), under the same conditions.

The structure, phase composition, and texture of the films were determined by

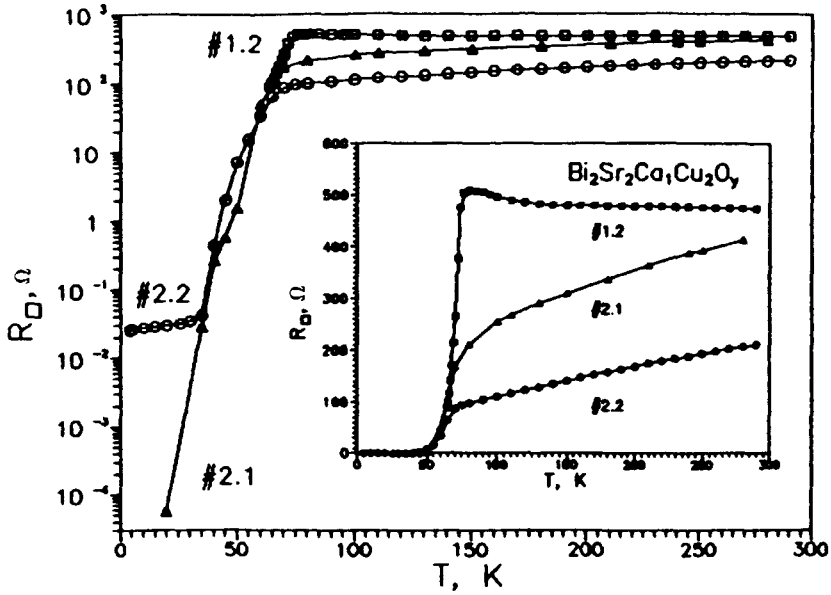

FIG. 3. Temperature dependence of the resistance of BSCCO films on an (Y,Nd)AlO_3 substrate (curves 2.1 and 2.2) and on a MgO substrate (1.2). The measurement current was $j \approx 3$ A/cm^2.

x-ray-structural analysis in Cu $K\alpha$ radiation. The resistance was measured by the standard four-contact method. The chemical formula of the films after the annealing was determined by electron microprobe analysis in a JEOL microscope.

4. Figure 1 shows x-ray diffraction patterns of films on (Y,Nd)AlO_3 and MgO substrates (films 2.2 and 1.2, respectively). Film 1.2 turned out to consist of two phases (2212 + 2201, with an average composition of $Bi_2Sr_{1.4}Ca_{0.7}Cu_{2.08}O_y$), while film 2.2 consisted of a single phase ($Bi_2Sr_{1.4}Ca_{1.07}Cu_{1.88}O_y$. The films were highly textured along the **c** axis. The lattice constants along **c** were different: $c=30.705$ Å for film 1.2, on MgO, and $c = 30.56$ Å for film 2.2, on (Y,Nd)AlO_3.

To determine the disorientation of the crystallites in the (**a, b**) plane, we recorded a φ scan of the 115 reflection of the 2212 phase (Fig. 2; the film was tilted $\chi=58.1°$ from the goniometer axis; the value of 2θ was 27.54°). For film 2.2, the four sharp peaks imply a high degree of orientation of the crystallites in the (**a, b**) plane (the disorientation of the axes is less than 1.2°). The identical intensities indicate that there is only one group of **a**-oriented crystallites. That the **a** and **b** directions of the film and the (Y,Nd)AlO_3 substrate are coaxial can be seen from the coincidence of the φ scans of the film 115_{2212} reflection and the substrate 112 reflection ($\chi=45°$, $2\theta=34.292°$). As can be seen from the φ scan of the 222 reflection ($\chi=54.7°$; $2\theta=62.4°$), the MgO substrate was fairly high in quality. Nevertheless, film 1.2, on MgO, has a random orientation of crystallites in the (**a, b**) plane: Its φ scan has no obvious peaks.

5. For all the films, the resistance transition begins at a low temperature [$T_{R\text{onset}} \approx 75$ K (Fig. 3); film 2.1 had the same chemical formula as 2.2 but differed in annealing temperature]. The reason is that film 1.2 was grown on an unpolished face of natural MgO, and for films 2.1 and 2.2 the annealing conditions were still far from optimal. Nevertheless, the films on the $(Y,Nd)AlO_3$ substrate have lower resistances, and the latter exhibit a metallic behavior.

Film 2.2 (the lowest-resistance film in the normal state) undergoes a 2500-fold decrease in resistance at the transition, and it begins to "become noisy," with 0.3-0.5 $\mu\Omega \cdot$ cm, at low temperatures. The resistance of film 2.1 in the normal state is higher than that of film 2.2. At $T = 20$ K it falls below 6.62×10^{-10} $\mu\Omega \cdot$ cm. Within this error, we can say that a dissipation-free superconducting state is established in film 2.1.

6. Single-phase superconducting films of $Bi_2Sr_2Ca_1Cu_2O_y$ have been grown on a $(Y,Nd)AlO_3$ substrate. The films can be classified as epitaxial, since they are **c**-oriented and have a clearly defined texture in their basal plane.

We wish to thank A. V. Zinovuk for measuring the resistances.

[1)]The lattice constants and crystallographic directions of the $(Y,Nd)AlO_3$ crystal are given in the orthorhombic system here.

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