Single-crystal films of high-temperature superconductors with the perovskite structure

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(Submitted 17 December 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 3, 157–159 (10 February 1988)

Single-crystal films of the superconductors $MBa_2Cu_3O_7$ (M = Y,Eu,Ho) with $T_c = 90.5$–91 K have been synthesized. The width of the resistive transition is 0.5–1 K. A sharp and complete diamagnetic transition is observed near 90 K. The resistivity at 100 K is 40–100 $\mu\Omega\cdot$cm. The critical current in liquid nitrogen is greater than 10^6 A/cm^2.

Experimental studies of the nature of high-temperature superconductivity are making effective use of bulk polycrystalline samples and also single crystals of metal-oxide superconductors.[1,2] For several applied and basic physics problems, however, it is necessary to synthesize high-quality film samples, including single-crystal films of these compounds. In the present letter we report the use of pulsed laser sputtering to synthesize single-crystal films of $YBa_2Cu_3O_7$, $EuBa_2Cu_3O_7$, and $HoBa_2Cu_3O_7$ with [001] direction running perpendicular to the plane of the film.

To synthesize films of high-temperature superconductors, we used the synthesis method developed in Refs. 3 and 4. In that method, the deposition takes from 0.5 min to several minutes for a film thickness of 0.1–1 μm, and no additional heat treatment is required. In the present experiments we used a solid-state laser with a pulse length of 10 ns and a repetition frequency of 50 Hz. The films were deposited on heated single-crystal $SrTiO_3$ substrates, with surfaces oriented perpendicular to the crystallographic [100] axis.

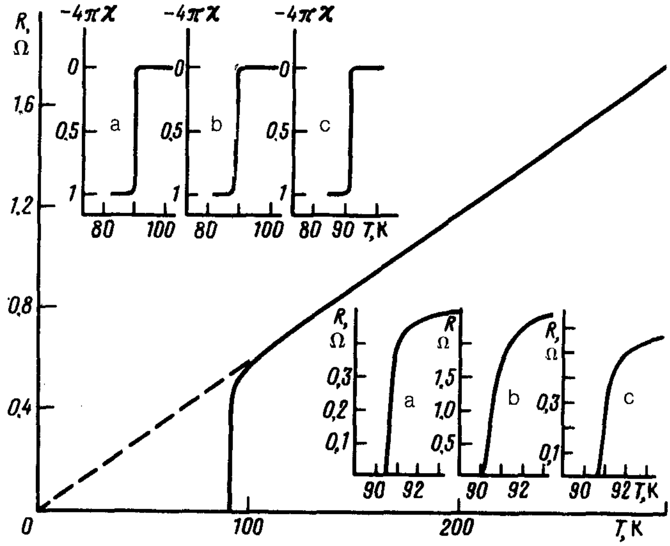

FIG. 1. Temperature dependence of the resistance of a single-crystal $YBa_2Cu_3O_7$ film. The lower inset shows curves of $R(T)$ in the vicinity of the superconducting transition for single-crystal films of (a) $YBa_2Cu_3O_7$, (b) $EuBa_2Cu_3O_7$, and (c) $HoBa_2Cu_3O_7$. The upper inset shows the temperature dependence of the magnetic susceptibility of the same samples.

Figure 1 shows the temperature dependence of the resistance, $R(T)$, for one of the single-crystal $YBa_2Cu_3O_7$ films synthesized. A four-contact method was used. A measurement current of 100 μa was passed in the [110] direction. As we see from this figure, an extrapolation of a linear dependence $R(T)$ in the normal state to the value $T = 0$ yields $R(T) = 0$. The resistivity at $T = 100$ K is 40–60 $\mu\Omega\cdot$cm. The part of the $R(T)$ curve near the superconducting transition is shown in larger scale in the lower inset in Fig. 1 (curve a). The complete disappearance of the resistance is observed at 90.4 K. The critical temperature T_c is 90.7 K. The width of the transition, between the levels of 10% and 90% of the resistance near the transition, does not exceed 0.5 K. The upper inset in Fig. 1 shows the temperature dependence of the magnetic susceptibility, $\chi(T)$, for the same sample, measured in an alternating magnetic field with an amplitude of 6.5 mOe and a frequency of 317 Hz (curve a). The sample goes diamagnetic abruptly at 90 K.

The lower inset in Fig. 1 (curves b and c, respectively) show $R(T)$ near the superconducting transition for single-crystal films of $EuBa_2Cu_3O_7$ and $HoBa_2Cu_3O_7$. Curves of $\chi(T)$ for the same samples are shown in the upper inset. We found $T_c = 90.5$ K for the europium compound and 91 K for the holmium compound. The resistance disappears at 90 K in the first case and at 90.7 K in the second. The resistivity of $EuBa_2Cu_3O_7$ film near the transition is 100 $\mu\Omega\cdot$cm, while that of the $HoBa_2Cu_3O_7$ film is 70 $\mu\Omega\cdot$cm. A sharp and complete diamagnetic transition occurs at 89–91 K.

The critical current of the $YBa_2Cu_3O_7$ film was determined from the appearance

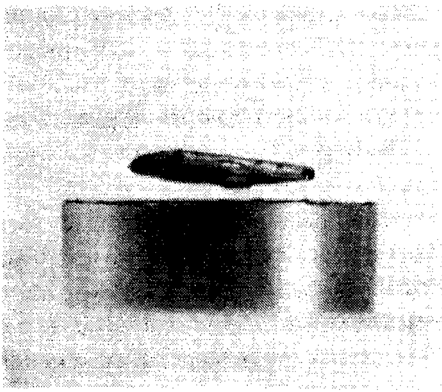

FIG. 2. A single-crystal $YBa_2Cu_3O_7$ film levitating above an annular magnet. The film was deposited on a strontium titanate substrate. The temperature was close to 90 K.

of a voltage of 1 μV across a narrow strip. At the boiling point of liquid nitrogen, this critical current was 1×10^6 A/cm^2 (this figure may be slightly on the low side because of the dissipation of a power of about 10 W at the current contacts). Cooled in liquid nitrogen and placed above a magnet in a field of 0.1–1 kOe, the film levitates with the substrate, whose mass is 10^3–10^4 times that of the film itself. Figure 2 is a photograph taken during this experiment. The film was deposited on the lower surface of the substrate. A drop of condensed oxygen can be seen under the sample.

Figure 3 is an x-ray diffraction pattern of one of the $YBa_2Cu_3O_7$ samples, recorded through the use of copper K_α radiation. On this pattern we see only the reflections of various orders from the (001) planes of the film and the (100) planes of the substrate. The films are single-crystal films. When we used substrates of the given orientation, the c axis ran perpendicular to the plane of the sample, as we mentioned earlier. We found no traces of foreign phases or inclusions of crystallites with a different orientation.

In the polycrystalline films which we synthesized on lithium niobate substrates under similar deposition conditions, the critical current and the conductivity in the normal state were lower than those of the single-crystal films grown on $SrTiO_3$. In such samples, on the other hand, it was possible to achieve values of T_c higher by 1–1.5 K (the width of the transition was 1.5 K, and complete superconductivity was reached at 89 K). These results are evidence that the $SrTiO_3$ substrate is influencing the structure of the film in a way which goes beyond its orienting effect.

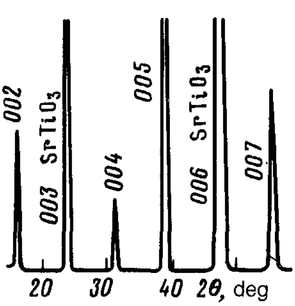

FIG. 3. x-Ray diffraction pattern of a single-crystal $YBa_2Cu_3O_7$ film.

The very first experiments on the synthesis of $LuBa_2Cu_3O_7$ films were rewarded with the synthesis of single-crystal samples with $T_c = 87.5$ K.

In summary, this development of the method of pulsed laser sputtering[3,4] has made it possible to achieve an epitaxial growth of single-crystal films of various high-temperature superconducting compounds with the perovskite structure. These films have a low resistivity in the normal state and high critical parameters.

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Translated by Dave Parsons