Anisotropy of magnetic and electric properties of thin superconducting $Y_1Ba_2Cu_3O_{7-\delta}$ films

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The high-T_c superconductor laser-deposited films with a current density of $\sim 10^6$ A/cm^2 are shown to have superconducting properties characteristic of single crystals. Anisotropy of the susceptibility $\partial\chi/\partial H$ and of the field $\partial H_{c2}/\partial T$, which correlate with each other, has been detected.

In this letter we discuss the results of experimental study of magnetic properties of Y-Ba-CuO films obtained by laser deposition[1] on a $SrTiO_3$ single-crystal substrate. The anisotropy of the upper critical magnetic field H_{c2} has been detected. The dynamic susceptibility χ and the critical current density j_c were also found to be anisotropic. The Ginzburg-Landau coherence length parameters $\xi_{\parallel}$ and $\xi_{\perp}$ were calculated on the basis of a model for layered superconductors.[2] We will show that in magnetic fields $H \sim H_{c2}(T)$ the susceptibility χ of the films depends essentially on the strength of the magnetic field H and that the following relation holds for all measured films:

$$(\partial\chi_{\perp}/\partial H)(\partial\chi_{\parallel}/\partial H)^{-1} \approx (\partial H_{c2\parallel}/\partial T)(\partial H_{c2\perp}/\partial T)^{-1}. \tag{1}$$

1. The measurements were carried out using Y-Ba-CuO films of thickness 0.2 μm. Three samples which differed in the technology used to synthesize them were used. The superconducting transition temperatures of these samples were respectively 88.4 K for sample 1, 90 K for sample 2, and 86 K for sample 3. Comparative measurements were carried out using ceramic disks of thickness 100 μm and 8 mm in diameter.

To measure H_{c2}, we placed the sample into an induction coil of the autodyne detector's tank. The coil containing the sample was situated in the anticryostat, whose temperature of the working volume could be varied from 77 K to 300 K. The variation of the autodyne's oscillation amplitude was recorded as a function of the temperature of the sample for various values of the external magnetic field. The deviation of the frequency due to the superconducting transition was singled out by means of a heterodyne and a "frequency-voltage" transducer. The change of the frequency in the experiment was attributed to the expulsion of the field from the film and to the change in its distribution in the coil. An appreciable redistribution of the field occurred when the film was displaced relative to the central plane of the coil. The signal associated with the superconducting transition increased markedly in this case. The temperature of the sample was measured within 0.01 K by a semiconductor thermometer and a copper-constant thermocouple. The magnetic field was produced by an electromagnet and measured by a Hall probe which was calibrated beforehand using an NMR magnetometer. The orientation of **H** parallel to the film was determined in a field $H \sim 10$ kOe at $T \lesssim T_c$ from the signal associated with the sample. The value of $T_c(H)$ was determined from the onset of the superconducting transition. In the working frequency interval 0.1–2 MHz the results of measurements did not depend on the frequency or the amplitude.

2. Figure 1 is a plot of the oscillator frequency variation as a function of temperature for certain values of H for sample 1. Figure 1a shows the case in which $\mathbf{H}\perp\mathbf{n}$ and Fig. 1b shows the case in which $\mathbf{H}\parallel\mathbf{n}$, where $\mathbf{n}$ is the normal to the film (curve 1 corresponds to the value $H = 0$ and curve 2 corresponds to the value $H = 10$ kOe). We see that for each orientation of **H** an increase in the field leads to a nearly parallel displacement of the transition curves toward lower temperatures. In contrast with the films, the superconducting transition in ceramic samples broadens as a result of application of an external magnetic field, and there is no anisotropy (the dashed curves). Figure 2 is a plot of the curves for $H_{c2\parallel,\perp}(T)$ for sample 1. We see that in fields of 2–15 kOe the $H_{c2}(T)$ curve is a linear function of the temperature for the case in which $\mathbf{H}\parallel\mathbf{n}$ and the case in which $\mathbf{H}\perp\mathbf{n}$. The value of the derivative $\partial H_{c2}/\partial T$ for a parallel field is 3.2 times greater than that for a perpendicular field. The anisotropy $(\partial H_{c2\parallel}/\partial T)(\partial H_{c2\perp}/\partial T)^{-1}$ for samples 1 and 3 is slightly lower, amounting to 2 and 1.3, respectively.

At temperatures close to $T_c(H)$ the susceptibility χ of the film increases markedly with increasing H. In fields $H > 3$ kOe the $\chi(H)$ curve is close to a linear curve and

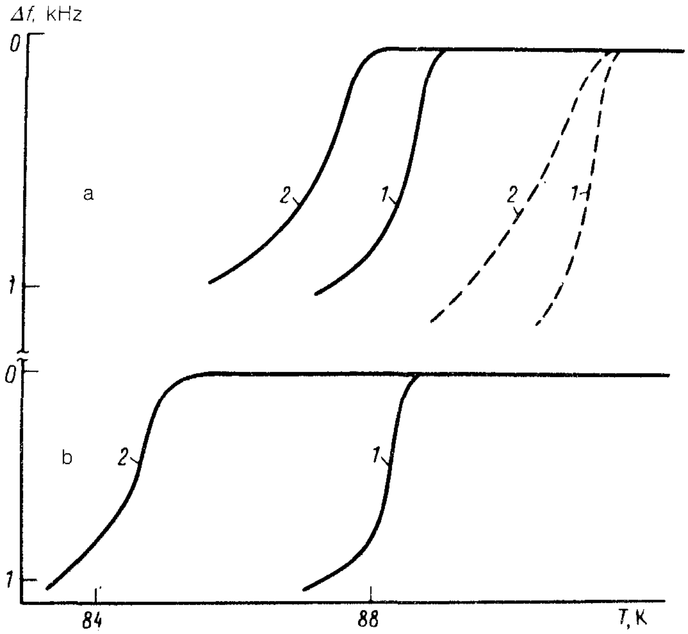
Δf, kHz
0
1
a
2
1
2
1
0
b
2
1
1
84
88
T, K

FIG. 1.

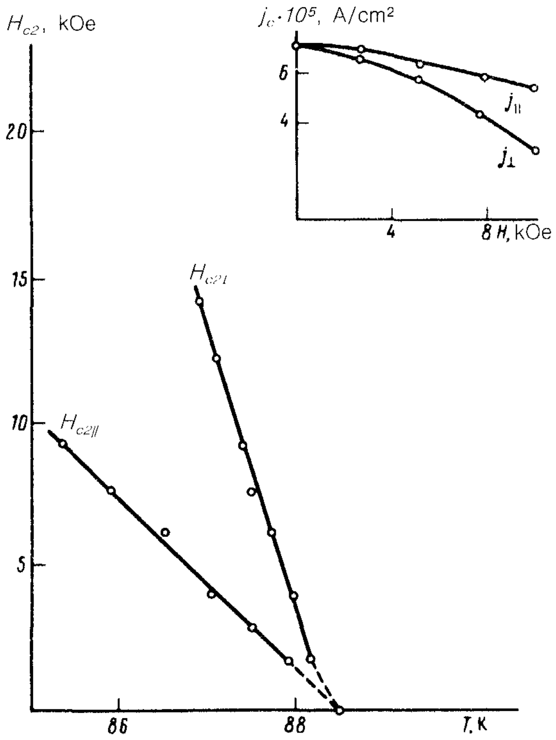
H_{c2}, kOe
20
15
10
5
86
88
T, K
$H_{c2\perp}$
$H_{c2\parallel}$
$j_c \cdot 10^5$, A/cm²
6
4
4
8 H, kOe
$j_\parallel$
$j_\perp$

FIG. 2.

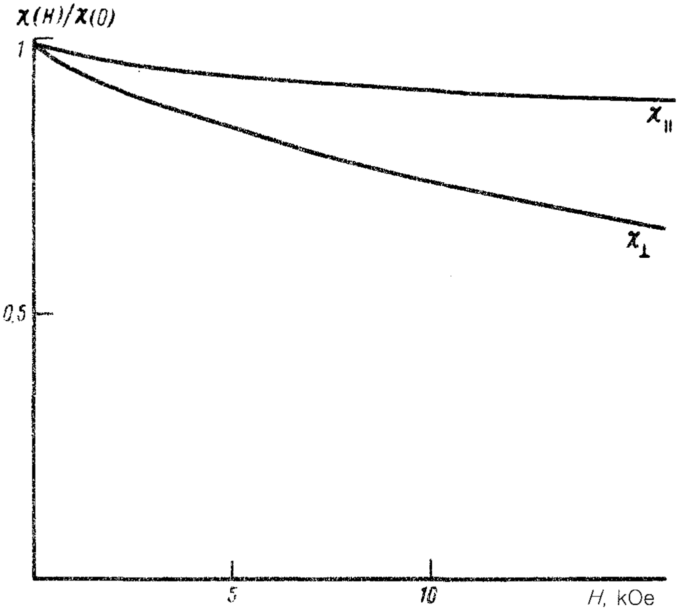

FIG. 3.

depends considerably on the orientation of the field (Fig. 3). In ~10-kOe fields the ratio $(\partial\chi_{\perp}/\partial H)(\partial\chi_{\parallel}/\partial H)^{-1}$ is 3.2 for sample 1. This ratio coincides within acceptable error margin with the ratio of the derivatives $(\partial H_{c2\parallel}/\partial T)(\partial H_{c2\perp}/\partial T)^{-1}$ for the same sample, i.e., relation (1) holds. Relation (1) holds also for samples 2 and 3.

We studied the angular dependence of $\partial\chi(\theta)/\partial H$ in a 10-kOe static magnetic field, where θ is the angle between the normal to the film and the direction of the magnetic field. The function $\partial\chi/\partial H$ decreases monotonically and smoothly with increasing θ and has a sharp minimum at $\theta=\pi/2$.

The critical current density in a magnetic field with $\mathbf{H}\perp\mathbf{j}$ is also anisotropic. The inset in Fig. 2 shows the $j_c(H)$ curve for $\mathbf{H}\|\mathbf{n}(j_{\parallel})$ and $\mathbf{H}\perp\mathbf{n}(j_{\perp})$. In fields up to 2 kOe the critical currents $j_{\parallel}$ and $j_{\perp}$ differ only slightly, but this difference increases with increasing H. In a 10-kOe field the ratio $j_{\parallel}/j_{\perp}$ is 1.6.

3. A comparison of the curves for the superconducting transition in single crystals[3] and in the test films shows that both materials have several common properties. In the first place, the transition width remains essentially constant upon application of a magnetic field, while the onset of the transition shifts toward lower temperatures. Secondly, the second critical field is found to be anisotropic. Since the inequality $\partial H_{c2\parallel}/\partial T > \partial H_{c2\perp}/\partial T$ holds for the films, we conclude that the data on the film have a preferred orientation of the c axis, which is parallel to the normal $\mathbf{n}$; i.e., the films which we have tested have a texture. This conclusion was confirmed by direct x-ray measurements. In contrast with the films, the behavior of ceramic samples in a magnetic field is considerably different (Fig. 1). In terms of their structure, the films hold the intermediate position between the ceramic and the single crystals.

The similarity in the properties of the textured films and Y-Ba-CuO single crystals allows the Ginzburg-Landau equations with an anisotropic "mass" to be used to estimate the superconducting parameters of these materials.[2] Extrapolating H_{c2} to zero temperature in the dirty limit of the BCS theory, in accordance with the data for sample 1, we obtain $\xi_{\parallel} = 39$ Å and $\xi_{\perp} = 11$ Å.

In analyzing the behavior of the susceptibility $\chi(H)$ we have taken into account that at $H \sim H_{c2}(T)$ we have $\chi \sim \xi^2$ according to the Ginzburg-Landau theory, whereas $H_{c2} \sim \xi^{-2}$. If $\chi H_{c2} = \text{const}$, a relation which holds for an isotropic superconductor, will also hold in the anisotropic case, then relation (1) is also expected to hold. A relation of this sort is derived from the analysis of the measurement data.

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