Magnetic properties and critical current of superconducting films $RBa_2Cu_3O_x$ (R = Y, Eu, Ho)

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The temperature dependence of the critical current density of single-crystal films of the high-temperature superconductors has been studied in parallel with the contactless (magnetic) methods and contact methods. The Bean model is shown to work well in magnetic fields up to 10^2 Oe, which are oriented perpendicular to the film plane.

The electrodynamic properties of high-temperature superconductors are of considerable interest from the general scientific point of view and from the point of view of applied science. It was demonstrated previously that the contactless magnetic methods are very useful for the study of these properties. Thus, for example, by measuring the temperature and field dependences of the magnetic moment M of bulk single crystals[1] and thin-film samples[2–4] it is possible to determine not only the temperature T_c of the transition to the superconducting state but also to measure quantitatively the temperature dependence of the critical current density j_c of these samples. However, a comparison of these data with those obtained by (electrical) contact measurements revealed certain discrepancies.[2,4] We present here the results of a study of the magnetic properties of thin films of high-temperature superconductors $RBa_2Cu_3O_x$ (R = Y, Ho, Eu) and compare the values of j_c and T_c which were obtained for the same samples by a contactless method and by direct electrical contact measurements.

The single-crystal films of the compositions closely related to $RBa_2Cu_3O_{7-\delta}$ (R = Y, Eu, Ho; $\delta \lesssim 0.5$), with a thickness d ranging from 0.15 μm to 1 μm and with the c axis oriented perpendicular to the plane of the $SrTiO_3$ single-crystal substrate, were fabricated by flash laser evaporation of ceramic targets of stoichiometric composition using a method described in Ref. 5. A part of the sample with the film shaped in

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the form of a square with a side $D \approx 1$ mm was cemented to a quartz filament and placed in a cell of a general-purpose SQUID magnetometer,[6] in which a wide dynamic range ($\gtrsim 130$ dB) was obtained by using an analog-digital operating regime of the SQUID electronics system. The magnetic moment of the film was measured during the slow warming of the sample in a static magnetic field H directed perpendicular to the plane of the film, after it was cooled down to liquid-helium temperature in a weak field $H' \lesssim 0.1\ H$.

In the case of all tested samples (see Table I), as the temperature is raised, the functional dependences $M(T,H)$ always reach, in the range of fields used by us $H \lesssim 10^2$ Oe, the asymptotic form $M_c(T)$, which is virtually independent of H (Fig. 1). A dependence of this sort is identified with any model describing a strong pinning of Abrikosov vortices on an unsaturated ensemble of inhomogeneities ("the Bean model"[7]),[2] which accounts for the independence of the critical current density j_c of the magnetic field H. The value of $j_c(T)$ for a square sample is found to be[1]

$$j_c(T) = -\frac{6}{D^3 d} M_c(T).$$

As can be seen in Fig. 1, the $j_c(T)$ curve is nearly linear, aside from the narrow temperature interval near T_c. This conclusion correlates well with the results of the

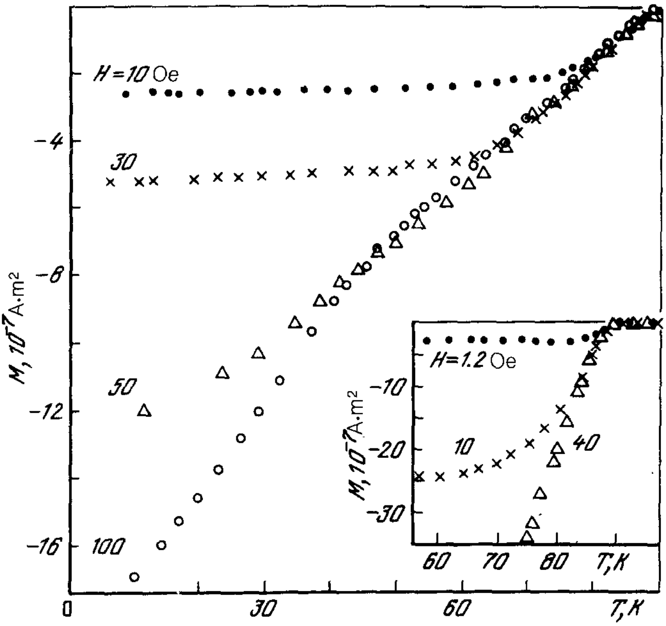

FIG. 1. Temperature dependence of the magnetization of the Ho–Ba–Cu–O–151 films ($D = 1 \pm 0.1$ mm, $d = 0.45 \pm 0.05$ μm) and Y–Ba–Cu–O–102 films ($D = 2 \pm 0.1$ mm, $d = 0.20 \pm 0.05$ μm, shown in the inset), obtained upon warming the samples in various magnetizing fields H, after cooling them in a field $H' \lesssim 0.1\ H$.

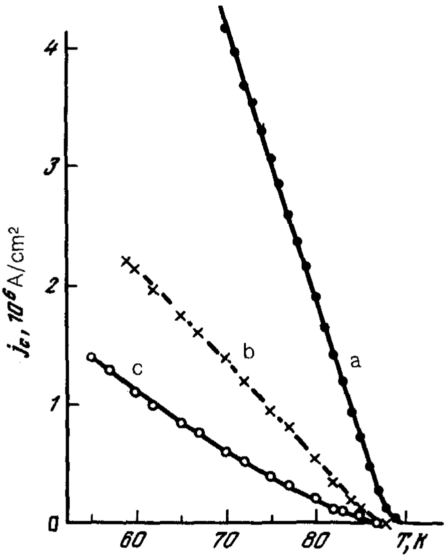

FIG. 2. Temperature dependence of the critical current density, obtained by means of electrical measurements of the following films: a—Ho–Ba–Cu–O–204; b—Y–Ba–Cu–O–170; c—Eu–Ba–Cu–O–177.

direct measurements of $j_c(T)$ (Fig. 2), which we have carried out by using the standard four-contact method (to carry out these measurements, we have cut out by using a sapphire cutting tool from a deposited film a microbridge measuring $\sim 0.2 \times 0.2$ mm or we have deposited through a mask a microbridge of the same dimensions).

The results of measurements of the values of j_c at $T = 77$ K, obtained by the two methods described above, are given in Table I. We see that these values can swing in either direction by several factors. The most likely cause of this difference is the macroscopic nonuniformity of the films on the surface of the substrate ($\sim 1 \times 1$ cm^2). Furthermore, in a contact method the considerable heating of the current contacts can cause the measured values of j_c to be lower than the true values.

TABLE I. Critical currents (in 10^5 A/cm^2) of single-crystal films of high-temperature superconductors ($T = 77$ K)[3].

Sample	Magnetic (contactless) measurements	Electrical (contact) measurements
Eu – Ba – Cu – O – 138	0.62	3.7
Eu – Ba – Cu – O – 177	8.0	2.0 – 4.0
Y– Ba – Cu – O – 102	11	–
Y – Ba – Cu – O – 170	1.7	2.3 – 7.5
Ho – Ba – Cu – O – 151	2,6	1.4
Ho – Ba – Cu– O – 204	–	26

We have compared the behavior of the $M_c(T)$ and $R(T)$ curves, which were measured by the methods indicated above, near T_c. We have also compared these curves with the $\widetilde{M}(T)$ curves for the screening of a weak alternating field by a film.[5] The values of M, $\widetilde{M}$, and R reach instrumental zeros at nearly the same points and at a point markedly lower (by 1–2 K) than the point T_{c0} at which the superconducting transition begins on the $R(T)$ curve. This result is more reasonable than that obtained in Ref. 4, where an appreciable diamagnetic response was reported to be present on the $M(T)$ curve up to temperatures much higher than T_{c0}.

The results of our study show that the magnetic properties of single-crystal films of the high-temperature superconductors $RBa_2Cu_3O_x$ (R = Y, Eu, Ho), whose c axis is oriented perpendicular to the plane of the substrate, are described well, at least in low fields ($\lesssim 100$ Oe), by the Bean model, and that the contactless magnetic method is a useful and reliable method of measuring T_c and the $j_c(T)$ curves.

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[2)]This conclusion was confirmed by our measurements of the Meissner effect, i.e., the $M^*(T)$ dependence, upon cooling the film, beginning with $T > T_c$, in a constant field H. At $H \approx 1$ Oe and $T \ll T_c$, for example, the values of M^* were only $\sim 1\%$ of those corresponding to the total shielding.

[3)]The intervals of the values of j_c correspond to the measurements of the different parts of the sample; the blank spaces mean that measurments based on one of the methods were not carried out.

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