The critical state and the H_{c1} field in $YBa_2Cu_3O_{7-x}$ single crystals

M. V. Kartsovnik, V. A. Larkin, V. V. Ryazanov, N. S. Sidorov, and I. F. Shchegolev
Institute of Solid State Physics, Academy of Sciences of the USSR

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The static magnetization of strongly twinned $YBa_2Cu_3O_{7-x}$ single crystals has been measured in weak fields. The critical current density of magnetization with an exponential temperature dependence has been determined. The anisotropy of the lower critical field H_{c1} is approximately equal to 6. The field H_{c1} increases linearly as the temperature is lowered to 40 K.

The anisotropic properties of high-temperature superconductors can be studied only in single crystal samples and oriented films. The $YBa_2Cu_3O_{7-x}$ single crystals which have so far been synthesized are generally imperfect and have small transverse dimensions. These factors determine the specific features of measurement of the anisotropic critical parameters of these materials.[1,2]

In this letter we report the results of the study of anisotropy and the temperature dependence of the lower critical field H_{c1} and the critical current density I_c of $YBa_2Cu_3O_{7-x}$ single crystals. The magnetic measurements in $\leqslant$400-G fields were carried out using an rf SQUID with a measuring sensitivity of the magnetic moment of better than 10^{-8} A·cm^2. We used single crystals grown from a nonstoichiometric melt of a mixture of oxides.[3] The crystals were heat treated in oxygen atmosphere, which greatly reduced the width of their superconducting transition. Before and after annealing, the crystals had a dense network of twins which was seen under a microscope in a polarized light. The crystals become twinned in two mutually perpendicular planes of the (110) type. In most of the samples the domains which twinned in different directions appeared in an alternating sequence, filling the crystal uniformly.

To determine the effect of the size of the crystals on the $M(H)$ curve, we cleaved one of the single crystals $0.8\times0.9\times0.03$ mm in size after subjecting it to a series of measurements. We have then run similar tests on one of the fragments measuring $0.5\times0.3\times0.03$ mm. Figure 1 shows a family of curves for the magnetization ($4\pi M$) versus the external magnetic field H_e for a fragment in a field $H_e \perp ab$. These curves were derived from the original $4\pi M(T)$ curves for the diamagnetic screening, measured in a fixed field specified at $T<10$ K. Typical curves for diamagnetic screening and Meissner expulsion into the field $H \| ab$ for a single crystal before and after annealing are shown in Fig. 2. A comparison with a lead reference frame showed that with $H \| ab$ the measured moment of the diamagnetic screening of single crystals is equal, within $\sim 10\%$ error, to the ideal diamagnetic moment of lead. To calibrate $4\pi M$ with $H_e \perp ab$ on the initial linear segments, we have therefore assumed $-4\pi M = H$ with $H = H_e/(1-D)$, where D is the demagnetization factor calculated under the as-

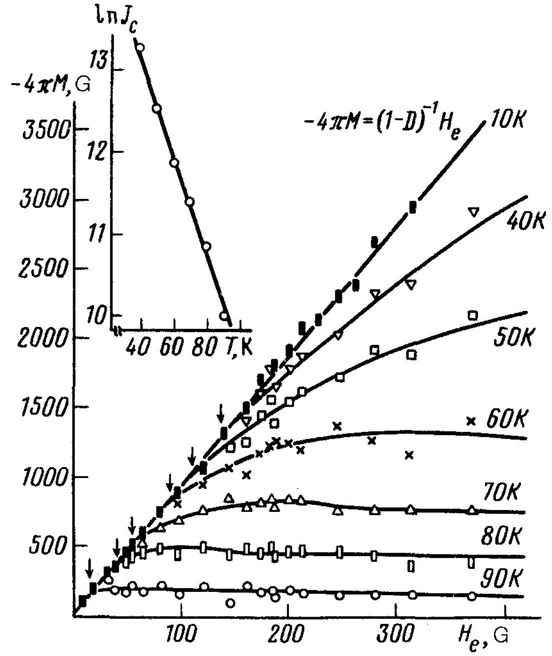

FIG. 1. The average magnetization versus the external magnetic field at various temperatures. The arrows indicate the external critical field $(H_e)_{c1}$. Solid curves—Calculation based on interpolation formula (1). The inset shows the temperature dependence of the critical magnetizing current.

sumption that the sample has an ellipsoidal shape. $D = 0.893 \pm 0.002$ for a single-crystal fragment and $D = 0.946 \pm 0.002$ for the original crystal.

Figure 3 shows the temperature dependence of the lower critical field H_{c1} (characterizing the onset of penetration of the flux into the sample) which is determined from the point $(H_e)_{c1}$ at which the $4\pi M(H_e)$ curve deviates from the initial linear behavior (Fig. 1). This point was determined by using an interpolation $4\pi M(H_e)$ curve, which is discussed below. The $H_{c1}^{\perp}(T)$ and $H_{c1}^{\|}(T)$ curves for the fragment and for the original single crystal are linear down to the temperature of 40 K, below which H_{c1} is difficult to extract from our results. A good agreement of the data for various crystals is evidence that it was correct to use the demagnetizing factor to take the

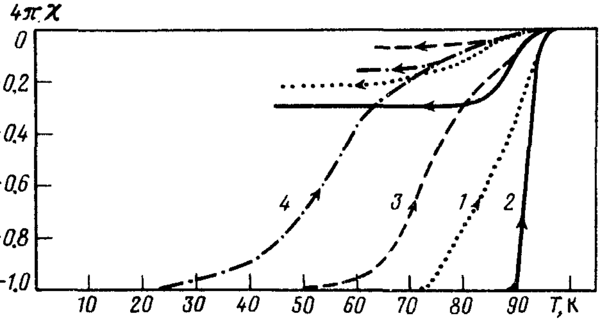

FIG. 2. The temperature dependence of the magnetic susceptibility for a diamagnetic screening and Meissner expulsion in the field $H\|ab$. 1—Nonannealed single crystal ($H = 5$ G); 2–4—the same single crystal after annealing ($H = 5$, 120, 292 G).

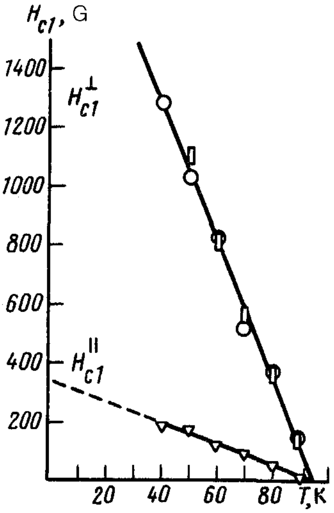

FIG. 3. Temperature dependence of $H_{c1}^{\perp}$ and $H_{c1}^{\parallel}$. Various points for $H_{c1}^{\perp}$ correspond to the original crystal and fragment.

effect of their size into account. The ratio $H_{c1}^{\perp}/H_{c1}^{\parallel} \approx 6$. At temperatures below 80 K the $H_{c1}(T)$ curve differs markedly from a well-known curve for conventional superconductors: $H_{c1} \sim [1-(T/T_c)^4]$ (see also Refs. 4 and 5). A linear extrapolation of H_{c1} to $T=0$ yields lower estimates of the penetration depth $\lambda_{\parallel}(0) \gtrsim 5\times 10^{-6}$ cm and $\lambda_{\text{l}}(0) \gtrsim 3\times 10^{-5}$ cm (for $\varkappa = 25$).

It can be seen from Fig. 1 that the $M(H)$ curves for 60 K$\leqslant T \leqslant$90 K reach a level $4\pi M_c(T)$, which is virtually independent of H_e. We attribute this behavior, like other investigators,[1,2,6] to a strong pinning of the Abrikosov vortices, which penetrate the sample. The penetration of the magnetic flux occurs gradually as the field at the sample's edge is increased.[7,8] When the flux reaches the midpoint of the sample, the magnetic moment stops increasing. Here the density of the superconducting screening current is equal to the critical current I_c at any point of the sample (we assumed I_c to be independent of H, since our experiments were performed in low fields). The inset in Fig. 1 shows the temperature dependence of I_c determined from the relation[7] $I_c = -30\, M_c/R$, which can be used[2] for a disk of radius R. Here I_c is measured in A/cm^2, M_c is measured in G, and R is measured in cm.

For a long cylinder in a field directed parallel to its axis, Bean[7] found the following relation for the average magnetization of the sample

$$-4\pi M = H + (H^2 - H_{c1}^2)/12\pi M_c - [H_{c1}^2(3H - 2H_{c1}) - H^3]/432\pi^2 M_c^2 \ . \quad (1)$$

Here H is the field strength of the sample. Clearly, we can substitute $H = H_e/(1-D)$ in Eq. (1) if the disk is magnetized uniformly, i.e., if the flux penetrates the sample only slightly. Calculation of the exact formula for M in the case of a nonuniform magnetization of a thin disk in a perpendicular field is a separate complex problem which generally cannot be solved analytically. We see, on the other hand, from Fig. 1 that relation (1), after the substitution indicated above, interpolates well the experimental data, at least in the interval $60\ \mathrm{K} \leqslant T \leqslant 90\ \mathrm{K}$, even in the case of a deep penetration of the magnetic flux into the sample. Assuming that interpolation formula (1) holds even at temperatures below 60 K, we can use it to refine the low-temperature values of H_{c1} and to determine the values of I_c in the temperature interval 40–60 K. As in Ref. 9, we have obtained an experimental dependence $I_c = I_{c0} \exp(-\alpha T)$, where $I_{c0} \approx 6 \times 10^6\ \mathrm{A/cm^2}$ and $\alpha = 6.2 \times 10^{-2}\ 1/\mathrm{K}$. (At $T = 70$ K the current density is $I_c = 0.9 \times 10^5\ \mathrm{A/cm^2}$.)

In summary, we have used the magnetization curves to plot the $H_{c1}(T)$ and $I_c(T)$ curves for $YBa_2Cu_3O_{7-x}$ single crystals. These curves differ considerably from the corresponding curves for ordinary superconductors. We have shown that the use of demagnetization factors is an effective method of taking into account the finite dimensions of the measured crystals.

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