# Temperature and angular dependences of the lower critical field in twinless $TmBa_2Cu_3O_{7-\delta}$ single crystals

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The temperature dependence of the lower critical field, $H_{c1}(T)$, of a twinless $TmBa_2Cu_3O_{7-\delta}$ single crystals is found to be linear over a very broad temperature interval. The angular dependence $H_{c1}(\varphi)$ has been studied and the values of $H_{c1}(0)$ along all crystallographic axes have been determined: $H_{c1}^{a,b,c}(0) = 250$, 300, and 1700 Oe, respectively.

The lower critical field $H_{c1}$ is one of the most important characteristics of type-II superconductors. The published data for oxide superconductors $RBa_2Cu_3O_{7-\delta}$, which were obtained using strongly twinned samples, are contradictory and incomplete.[1–3] The presence of a twinning structure in these compounds hinders the study of the

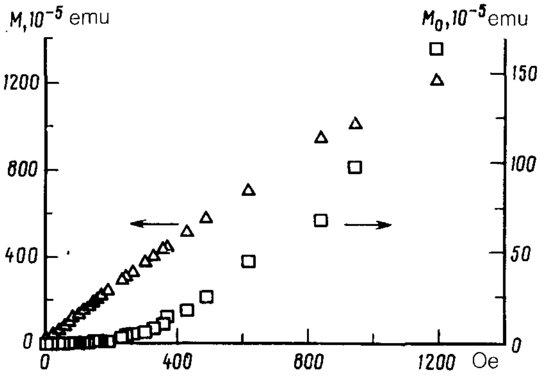

FIG. 1. Field dependence of the magnetization and of the captured magnetic moment of a $TmBa_2Cu_3O_{7-\delta}$ single crystal (Tm4 sample) ($H \| c$, $T = 9.7$ K).

anisotropy of their properties and may radically change the superconducting properties because of the weak coupling between the twins.

Twinless $TmBa_2Cu_3O_{7-\delta}$ single crystals were synthesized from nonstoichiometric mixtures $Tm_2O_3$–BaO–CuO by the molten-solution method.[4] The wafer-shaped crystals were 0.5–1 mm long and 30–100 $\mu$m thick. The domain structure was controlled by visual observation under a polarizing microscope with a resolution of $\sim 1$ $\mu$m.

The lower critical field corresponds, as we know, to the onset of penetration of the Abrikosov vortices into the sample. The point at which the magnetization curves $M(H)$ begin to deviate from linearity is usually used to determine $H_{c1}$. In the case of strong pinning this deviation near $H_{c1}$ is very slight, causing a large error in measuring $H_{c1}$. The value of $H_{c1}$ in this case can be determined from the point at which a trapped nonzero magnetic moment $M_0$ forms after the introduction and removal of the field. As can be seen from Fig. 1, this method is much more sensitive than the standard method, because the onset of a trapped moment is easier to detect than to measure the point at which an $M(H)$ curve begins to deviate from linear behavior. At high temperatures both methods give the same results as the flux pinning decreases.

Figure 2 shows the temperature dependences of $H_{c1}(T)$ for Tm4 sample with $H \| c$ and $H \| a$. This sample, measuring $0.9 \times 0.6 \times 0.05$ mm, is $\approx 80\%$ single-domain sample and does not contain any twins. At $T > 10$ K the $H_{c1}$ curves are nearly linear for the two orientations. At $T > 40$ K the $H_{c1}(T)$ curve was also found in Refs. 2 and 3 to be linear for $YBa_2Cu_3O_{7-\delta}$ twin single crystals. At lower temperatures the values of $H_{c1}$ were not measured because of the strong pinning. The low-temperature part of the $H_{c1}(T)$ curve for the TM1 sample is shown in the inset in Fig. 2. This sample, $1.1 \times 0.9 \times 0.1$ mm in size, is about 75% single-domain sample. As can be seen in Fig. 2, the $H_{c1}$ curve reaches saturation only at temperatures $T < 10$ K.

The presence of large twinless regions has made it possible to determine the values of $H_{c1}$ for various crystallographic directions. At $T = 10$ K the values of 250, 300, and 1700 Oe were obtained for a Tm4 sample for the *a*, *b*, and *c* axes, respectively. Making use of the correlation length $\xi_{\|} = 0.51$ nm and $\xi_{\perp} = 3.1$ nm (Ref. 5), we calculated the penetration depth $\lambda_a \approx 60$ nm, $\lambda_b \approx 70$ nm, and $\lambda_c \approx 64$ nm from the

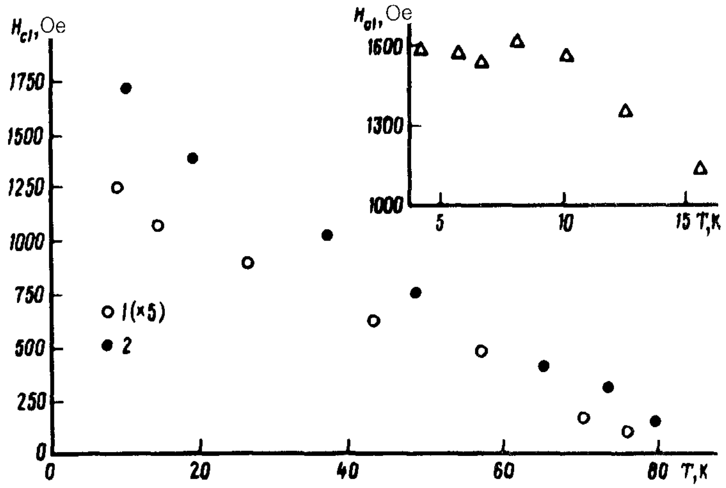

FIG. 2. Temperature dependence of the lower critical field of Tm4 sample ($1 - H\|a$; $2 - H\|c$). The inset shows the plot of $H_c(T)$ of a Tm1 sample at low temperatures ($H\|c$).

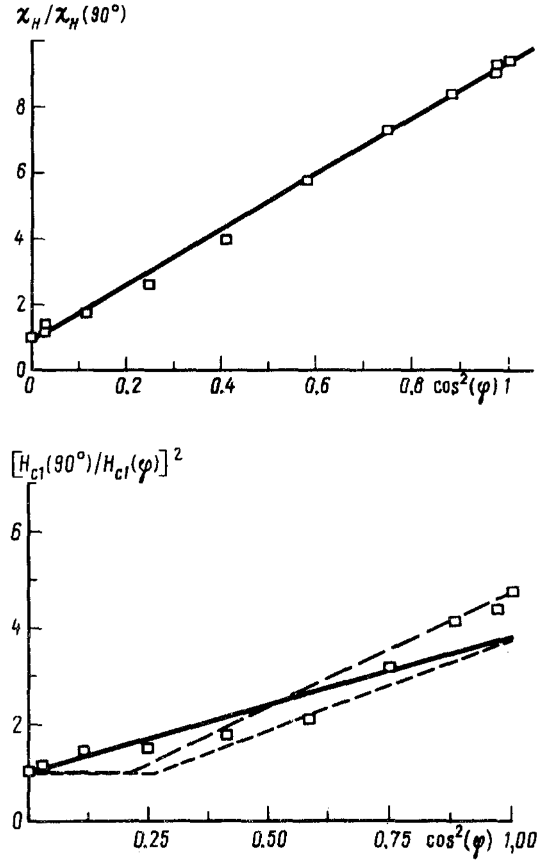

FIG. 3. Reduced Meissner susceptibility $\chi_H(a)$ and the inverse square of the applied lower critical field $H^e_{c1}$ ($b$) vs $\cos^2\varphi$ for a Tm4 sample ($T = 10$ K). The solid curve in Fig. 3b corresponds to a calculation based on a model of Balatskiĭ *et al.*[6] for $\mu = 26$; the dashed curves correspond to a calculation based on Klemm's model:[8] extended-dash curve—$\mu = 33$, $\varkappa_< = 380$; dashed curve—$\mu = 50$, $\varkappa_< = 100$.

relation $H^{(k)}{}_{c1} = (\Phi_0/\lambda_i\lambda_j)\left[\ln\sqrt{(\lambda_i\lambda_j/\xi_i\xi_j)} + 0.497\right]$ (where $i$, $j$, and $k$ are the various components along the crystal axes).

Measurements of the angular dependence of the susceptibility in the Meissner phase for the $b$–$c$ plane showed that this curve is, as can be seen from Fig. 3, nearly linear in $\cos^2\varphi$, where the angle $\varphi$ is reckoned from the $c$ axis. Such a curve is usually associated with a superconducting ellipsoid. The component of the magnetic susceptibility in the magnetic field direction (which is measured experimentally) in this case is given by

$$\chi_{H} = -\left[1+(n-1)\cos^2\varphi\right]/(1-N_b), \tag{1}$$

where $n = (1-N_b)/(1-N_c)$, and $N_c$ and $N_b$ are the demagnetizing factors along the $b$ and $c$ axes. The experimental results and theoretical dependence obtained by the least-squares method using Eq. (1) is shown in Fig. 3. The experimental data for a sample with a shape of a thin wafer are in good agreement with the results of a calculation in an ellipsoidal approximation. Furthermore, the value $n = 9.5 \pm 0.5$ obtained from the experimental data is nearly the same as the value calculated on the basis of the demagnetizing factors for the inscribed ellipsoid: $n = 9.84$. Accordingly, our results, as well as the data of Ref. 2, show that the ellipsoidal approximation works well for thin wafer samples.

For uniaxial anisotropic superconductors the angular dependence $H_{c1}$ in the absence of demagnetizing effects was calculated by Balatskiĭ *et al.*:[6]

$$H_{c1}(\varphi) = H_{c1}(0)/(\cos^2\varphi + \mu\sin^2\varphi)^{1/2}, \tag{2}$$

where $\mu = m_{\parallel}/m_{\perp}$ is the effective-mass anisotropy, and the symbols $\parallel$ and $\perp$ correspond to the direction along the axis of rotation and at right angles to it. As the measurement results have shown, the anisotropy of $H_{c1}$ in $\mathrm{TmBa_2Cu_3O_{7-\delta}}$ is slight in the $ab$ plane. This circumstance allows us to use expression (2), substituting as $m_\perp$ the mass along the axis under study. The demagnetization effects can be easily taken into account in the ellipsoidal approximation by means of the relation

$$H_{b,c}^{(i)} = H_{b,c}^{(e)}/(1-N_{b,c}), \tag{3}$$

where the indices $i$ and $e$ represent respectively the internal and external applied fields. Using Eqs. (2) and (3), we find the expression for the external field which accounts for the destruction of the Meissner phase

$$H_{c1}^{(e)} = H_{c1}^{(e)}(0)/(\cos^2\varphi + n^{-2}\mu\sin^2\varphi)^{1/2}, \tag{4}$$

where $H_{c1}{}^{(e)}(0) = H_{c1}{}^{(i)}(0)(1-N_c)$.

As can be seen from Fig. 3, the experimental data are in satisfactory agreement with expression (4) when $\mu = m_c/m_b = 26$. Note that the anisotropy $m_c/m_b = 31$ was found from the measurements of $dH_{c2}/dT$ along the $b$ and $c$ axes.[7] A slightly better agreement between the calculated and experimental data on $H_{c1}(\varphi)$ can be obtained by using the model proposed by Klemm.[8] This model, which is based on the variational method, makes it possible to go beyond the scope of a logarithmic approximation.[6] The presence of two variable parameters—the mass anisotropy $\mu$ and the

Ginzburg-Landau parameter, $\varkappa_< = \lambda_b/\xi_b$—leads to a considerable arbitrariness in determining them.

In conclusion, we should emphasize that the linear temperature dependence of the lower critical field is the most unusual result that we have obtained. This result, obtained with use of single-domain samples, has been confirmed by many data for polydomain samples,[2,3] and it suggests that such a dependence is an intrinsic property of high-$T_c$ superconductors which is not related to the presence of twin boundaries. At the same time, at $T < 50$–$60$ K the penetration depth, $\lambda^{-2} \sim H_{c1}$, no longer depends on the temperature.[9] The nature of such a peculiar behavior of the $H_{c1}(T)$ and $\lambda(T)$ curves is not clear at this time.

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