Magnetic Hysteresis of $YBa_2Cu_3O_{7-x}$ Single Crystals in Very High Magnetic Fields above 100 T

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Magnetic hysteresis of single crystals of $YBa_2Cu_3O_{7-x}$ was measured in pulsed high magnetic fields above 100 T. The data were analyzed taking into account the temperature increase due to the application of pulsed fields. It is argued that values of magnetic fields at which the magnetic hysteresis disappears can be reasonably interpreted as B_{c2} at low temperatures. The estimated upper critical fields at absolute zero were $B_{c2}^{\parallel}(0)=40\pm5$ T and $B_{c2}^{\perp}(0)=110\pm10$ T, which leads to an anisotropy ratio of about 3.

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The upper critical field B_{c2} is one of the most important properties of type-II superconductors. There have already been a great number of investigations for the determination of the upper critical fields of high-T_c oxide superconductors.[1] B_{c2} of $YBa_2Cu_3O_{7-x}$ (Y-Ba-Cu-O) is very high and anisotropic. Direct measurements of $B_{c2}^{\perp}(T)$, the upper critical field perpendicular to the c axis, need ultrahigh magnetic fields over 100 T. Therefore, the measurements of $B_{c2}^{\perp}$ have been limited so far to a narrow temperature range near T_c and data have been extrapolated to $T=0$ K.

Recently, however, it has been argued by many authors[2-4] that conventional methods to determine B_{c2} near T_c are subject to the so-called thermally assisted flux flow and give lower values than the true B_{c2}. Therefore, it is very important to directly measure B_{c2} at low temperatures. We measured the magnetic hysteresis for a powdered sample of Y-Ba-Cu-O in ultrahigh magnetic fields produced by the single-turn coil technique,[5] and showed that B_{c2} at low temperatures was really over 100 T.[6]

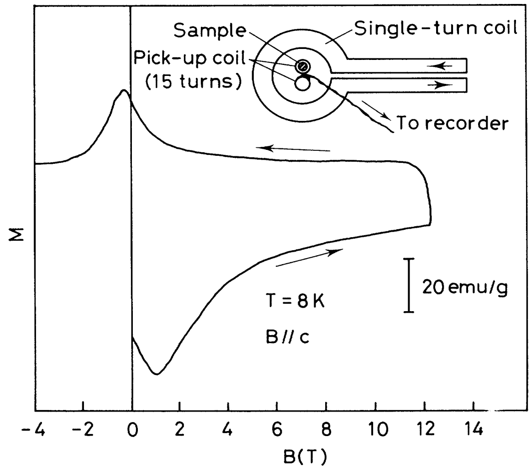

FIG. 1. Magnetization curve in a pulsed magnetic field generated by the single-turn coil system. The rise time of the pulsed field is 2.5 μs. The inset schematically shows the principle of the magnetization measurement by the induction method in a single-turn coil.

In this paper, we present data for single crystals of Y-Ba-Cu-O in a wide temperature range down to 28 K. Single crystals of Y-Ba-Cu-O were grown by a flux method.[7] We used an assembly of twelve thin crystals with a typical size of $1\times1\times0.2$ mm^3. The total weight of the crystals was 10.7 mg.

The magnetization measurements were done using the induction method, as has already been reported.[6] Although the rise time of the pulse is as short as 2.5 μs, it is confirmed that the magnetization curve in the low-field region can be measured as shown in Fig. 1. The shape of the magnetization curve is characteristic of the type-II superconductor in the critical state,[8] and is similar to that measured in much longer pulsed fields or steady fields.[9] Figure 1 clearly shows that the critical state is realized even in a very rapid field change (5×10^6 T/s). In the higher-field range (> 40 T), however, the measurement of the magnetization becomes very difficult because the single-turn coil is deformed by the magnetic force and the field distribution around the pickup coil becomes time dependent. Therefore, a spurious signal is induced in the pickup coil, and the integration of the measured voltage does not necessarily give the true value of the magnetization.

Nevertheless, we can accurately measure the hysteretic component of the magnetization curve under ultrahigh magnetic fields by the following procedure. As is shown in Fig. 1 the magnetization curve of Y-Ba-Cu-O can be well described by the critical-state model and shows a steep change at the maximum of the magnetic field. This magnetization jump induces a voltage pulse in the pickup coil. An example of the induced voltage in a high-field pulse is shown in Fig. 2 together with a trace of the magnetic field. There can be seen a well-defined peak just after the magnetic field reaches its maximum. Integrating the voltage peak, we obtain the value of the magnetization jump ΔM at the maximum value of the

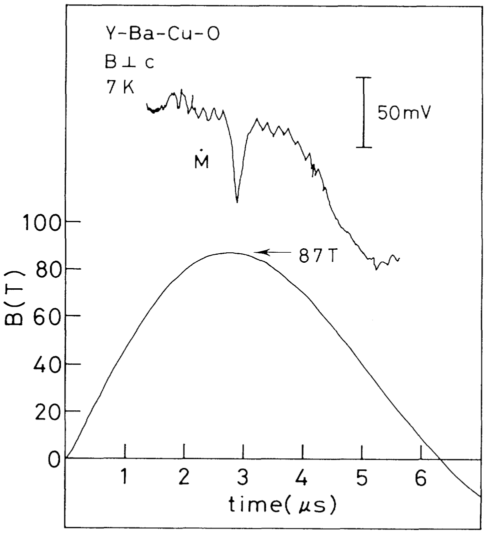

FIG. 2. Example of the measurement in a high field. The upper trace shows the induced voltage in the pickup coil. The lower trace shows the applied field.

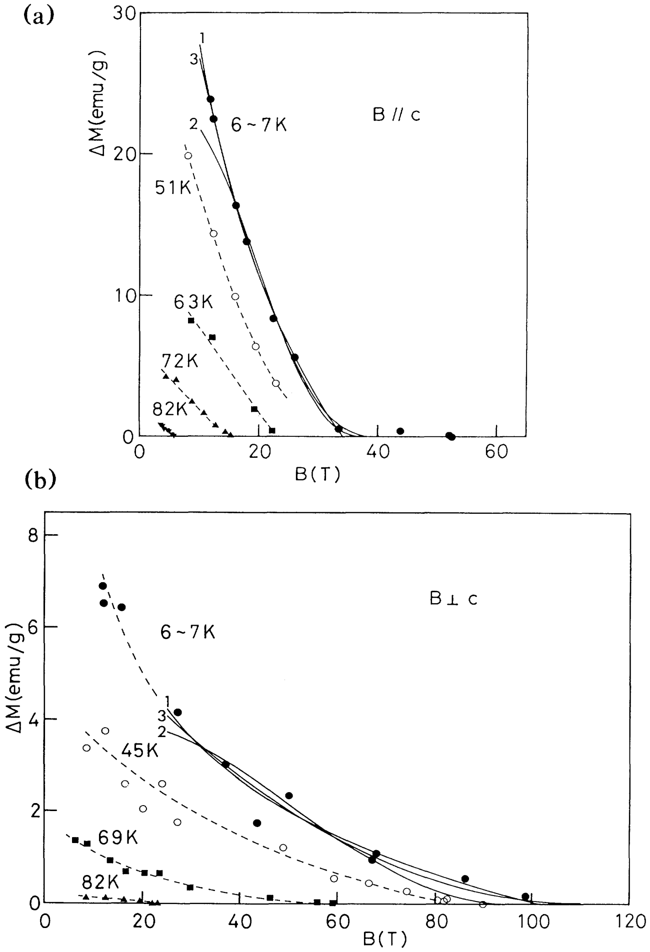

FIG. 3. Magnetic hysteresis as a function of magnetic field (a) parallel and (b) perpendicular to the c axis. Each experimental curve is labeled by the starting temperature. The estimated temperatures at the highest field for each experimental curve are 33, 53, 64, 72, and 82 K for $B \parallel c$, and 28, 46, 69, and 82 K for $B \perp c$. Solid curves are best-fit results with the following functional forms: 1, $J_c \propto (1-b)b^{-1/2}$; 2, $J_c \propto (1-b)^2 b^{1/2}$; and 3, $J_c \propto (1-b)^2$. Broken curves are guides to the eye.

pulsed field. We plot the thus determined ΔM in Fig. 3 as a function of magnetic field. Each experimental point is obtained from an independent measurement under a pulsed field with various maximum values. The existence of the magnetic hysteresis which is characteristic of the critical state provides evidence of the superconductivity. It should be noted that this type of magnetic hysteresis cannot be induced by the contribution of normal carriers. In the present work we determine the value of the magnetic field B_0 at which the magnetic hysteresis disappears by a fitting procedure.

In a conductive material, application of pulsed magnetic fields induces a Joule heating due to the eddy current. In the type-II superconductors, application of pulsed high fields forces flux lines to move within the sample, and this process dissipates energy. The work W done to a unit volume of the material in one cycle of the applied field pulse is expressed by

$$W = \oint H\, dM\,, \tag{1}$$

which is proportional to the area of the magnetic hysteresis curve. Therefore, we can evaluate the dissipated energy from Fig. 3 on the assumption that the main contribution to the hysteresis comes from the flux-pinning effect. This assumption was verified at least in the lower-field region as is demonstrated in Fig. 1. If the duration of the pulsed field is so short that cooling by the heat bath cannot be expected, as in the present experiment, the sample temperature is increased. We can estimate the temperature increase as a function of magnetic field from (1) together with the data of the specific heat.[10] When the starting temperature is low, the temperature increase is large because the specific heat is small and the magnetic hysteresis is large. The temperature increase shows a strongly saturating behavior after an initial steep increase.[11] When the starting temperature was 6 K (the lowest starting temperature in the present experiment), the temperature was increased up to 28 and 33 K in the fields perpendicular and parallel to the c axis, respectively. When the starting temperature was higher than 60 K, however, the temperature increase was estimated to be less than 1 K. In Fig. 3, measurements with the same starting temperature are represented by the same symbol.

According to the critical-state model, the magnetic hysteresis is proportional to the critical current density J_c. There is no well established model for the pinning mechanism of flux lines in Y-Ba-Cu-O yet. Campbell[12] proposed a simple model in which the magnetic field dependence of J_c is expressed by the following relation:

$$J_c \propto (1-b)b^{-1/2}, \tag{2}$$

where $b=B/B_{c2}$ is the reduced magnetic field. In the present analysis, we interpret b as B/B_0 and retain the possibility that B_0 is smaller than true B_{c2}. Recently, van den Berg *et al.*[13] proposed a model in which flux lines parallel to the c axis are pinned by twin boundaries and J_c depends on b as

$$J_c \propto (1-0.29b)(1-b)^2 b^{1/2}. \tag{3}$$

Kes *et al.*[14] deduced another functional form whose field dependence is reduced to that of Campbell under a large B_{c2}. Generally, there are many other possible functional forms of J_c depending on the details of the pinning mechanism.[15] Among them, we can arbitrarily choose a simple functional form

$$J_c \propto (1-b)^2 \tag{4}$$

as the third candidate.

We tried to fit the experimental curves in Fig. 3 by these three functional forms. Sample temperatures are increased more or less from starting temperatures, and the temperature increase is a function of magnetic field. Therefore, the experimental curves in Fig. 3 cannot be considered to be isothermal curves. However, the temperature increase saturates rapidly as is mentioned before. Therefore, we used only the experimental points of high fields ($b > 0.3$) in the fitting procedure. In the case of relation (3), a less important factor $(1-0.29b)$ was removed for simplicity. The best-fit results are shown in Fig. 3 by solid curves for the lowest temperatures. The same analysis was carried out for all the curves for higher temperatures (not shown).

B_0 values determined by the above procedure are plotted in Fig. 4 as a function of temperature, where the temperature increase is taken into account. Error bars represent the difference between the values obtained using the three dimensional forms. The three kinds of functional forms fit the data equally well, so that we cannot determine the best one to explain the experimental results. Solid curves represent B_{c2} obtained resistively by Sakakibara *et al.*[16] for a single crystal which has properties similar to those of the crystals used in the present experiment. The present result gives slightly higher values than those determined resistively in the case of $B \parallel c$.

Recently, the thermally activated flux flow (TAFF) has been considered to play an important role in the properties of high-T_c superconductors.[2] Malozemoff *et al.*[3] compared the values of B_{c2} obtained by different techniques and concluded that the B_{c2} vs T curve determined by measuring the magnetoresistance or ac susceptibility should be regarded as the "irreversibility curve." According to their idea, it is substantially smaller than the true B_{c2}, especially when the measurement is performed at a low frequency. Our technique measures the magnetic hysteresis and determines magnetic fields B_0 at which it disappears. Therefore, one may suppose that our technique is subject to the TAFF problem mentioned above and B_0 is smaller than B_{c2}. However, the difference between B_0 and B_{c2} cannot be caused only by TAFF. The process of TAFF may reduce the magnitude of the magnetic hysteresis by making some flux lines creep during the measuring time. As is well known, the creep speed decreases drastically when the gradient of the flux-line density decreases from the critical-state value. Hence, a finite value of the magnetic hysteresis must be observed even when TAFF exists, although the value may be reduced by TAFF depending on the characteristic time scale of the measurement. This is the most important difference between our technique and the measurement of the magnetoresistance or the ac susceptibility where the onset of the flux creep rather than the final disappearance of the flux density gradient is detected.

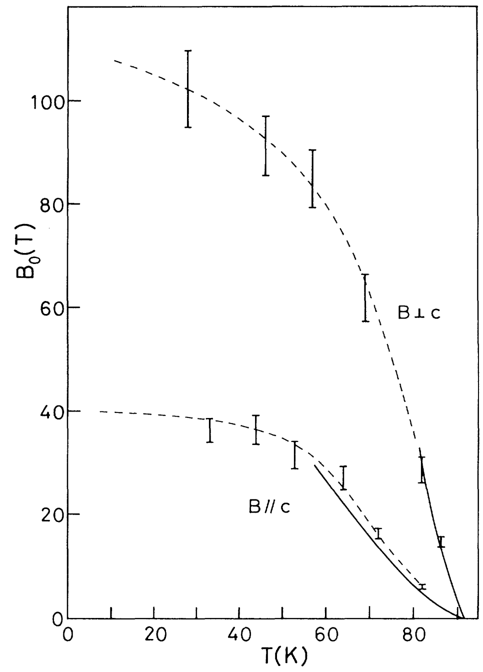

FIG. 4. Anisotropic B_0 as a function of temperature. Solid curves show resistively determined B_{c2} (from Ref. 16). Broken curves are guides to the eye.

Very recently, Welp *et al.*[17] observed reversible magnetization in Y-Ba-Cu-O in a temperature range of about 8 K below T_c. In the field of 4 T parallel to the c axis, the reversibility persisted down to 81 K at least. In our measurement, however, a pronounced magnetic hysteresis was observed up to 5 T at 82 K, as is shown in Fig. 3(a). These experimental facts do not necessarily conflict with each other if the large difference in time scales of the two measurements is taken into account.

Therefore, irrespective of the existence of TAFF, B_0 should coincide with B_{c2} in principle unless some other mechanisms give rise to a discontinuous change of hysteresis as a function of field at some point, and introduce ambiguity into the fitting procedure.

We cannot exclude the possibility that the pinning force F_p is not a smooth function of B, but is a function which decreases steeply to an undetectably small value at a low field and then decreases gradually to zero at B_{c2}. In such a situation our technique would detect the steep decrease of F_p rather than the final disappearance of F_p at B_{c2}. Gammel *et al.*[18] suggested the existence of the melting of the flux-line lattice in Y-Ba-Cu-O. This process can cause the steep decrease of the pinning effect within the superconductive region. However, Gammel *et al.* observed melting temperatures below T_c only in fields parallel to the c axis but not in fields perpendicular to it.

In our data, the field $B_0(T)$ at which the hysteresis disappears shows a saturating behavior with decreasing temperature. This behavior is very difficult to explain if there is a significant contribution of TAFF or flux-lattice melting because both effects should be strongly temperature dependent. Therefore, we believe that at least at low temperatures below about 60 K, where the $B_0(T)$ shows a saturating behavior, it is quite reasonable that $B_0(T)$ is very close to $B_{c2}(T)$. At high temperatures near T_c, we may have to be subject to the effect of TAFF and the flux-lattice melting.

In conclusion, we measured the magnetic hysteresis of single crystals of Y-Ba-Cu-O under pulsed fields above 100 T, and deduced $B_0(T)$ in a wide temperature range down to 28 K. If we extrapolate $B_0(T)$ to absolute zero, we obtain $B_0(0)$ to be 40 ± 5 T for the field parallel and 110 ± 10 T for the field perpendicular to the c axis. On the assumption that $B_0(0)$ is identical with $B_{c2}(0)$, the anisotropy of $B_{c2}(0)$ is about 3. This value is significantly smaller than estimated in previous works.[1] It should be noted, however, that this anisotropy factor of 3 is very close to the recent report of the anisotropy in H_{c1}.[19]

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