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The upper critical field and the normal-state resistivity of $YBa_2Cu_3O_{7-\delta}$ thin films in megagauss fields

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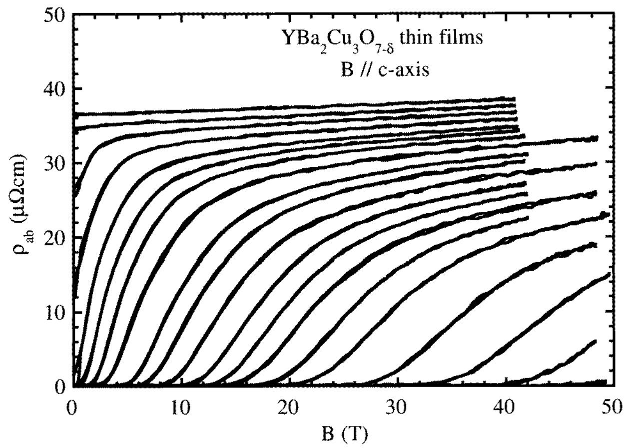
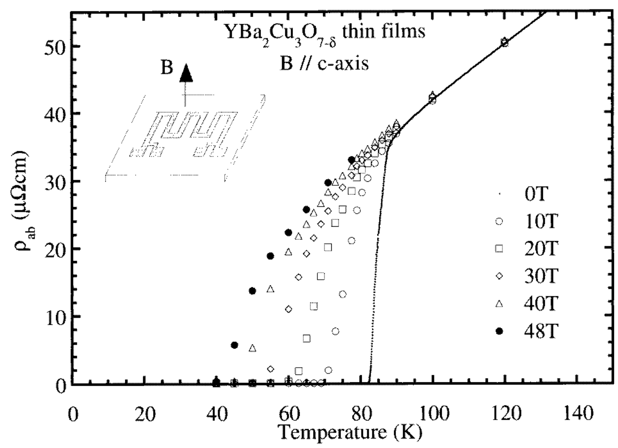
Abstract. We measured the DC and AC magnetoresistance of $YBa_2Cu_3O_{7-\delta}$ thin films at temperatures between 4.2 K and 100 K in magnetic fields parallel to the *c*-axis of up to 130 T. By minimizing the sample size and the area of the measurement circuit perpendicular to the magnetic field, a very good signal-to-noise ratio was obtained using a high-frequency digital lock-in technique for the AC measurements. Suppressing the superconductivity down to 4.2 K using magnetic fields up to 130 T, we found that the normal-state resistivity remains metallic down to 4.2 K. We determined the upper critical fields (H_{c2}) down to 4.2 K; H_{c2} tends to saturate at low temperature.

Recently, the unusual properties of the normal state of high-T_c superconductivity have been studied intensively. One of the unusual normal-state properties is the anisotropic temperature dependence of the resistivity. The in-plane resistivity ρ_{ab} decreases linearly with decreasing temperature over a wide range of carrier concentration, while the out-of-plane resistivity ρ_c increases rapidly at low temperatures [1, 2]. It is widely believed that the unusual properties of the normal-state resistivity reflect the electronic structure of high-T_c superconductivity. It is an open question whether this contrasting behaviour of ρ_{ab} and ρ_c extends to low temperatures or not. There are two ways to measure normal-state properties while suppressing the superconductivity. One way to suppress the superconductivity is by means of chemical substitution [3, 4] and another is to utilize an intense magnetic field [5–7]. Up to now, there have been few experiments using high magnetic fields because of the very large upper critical field (H_{c2}) of the high-T_c cuprates. Recently, some measurements of the normal-state resistivity below T_c using pulsed fields of up to 60 T were reported for $La_{2-x}Sr_xCuO_4$ (LSCO) [5, 6] and La-doped $Bi_2Sr_2CuO_y$ (Bi-2201) [7]. It is reported that in LSCO the contrasting behaviour of ρ_{ab} and ρ_c does not persist to low temperature, while in slightly overdoped Bi-2201 the contrasting behaviour was observed at low temperature. It is important to measure the normal-state resistivity below T_c in other high-T_c cuprates over a wide range of carrier concentration.

In this paper we report on DC and AC magnetoresistance measurements on *c*-axis-oriented thin $YBa_2Cu_3O_{7-\delta}$ films made using the single-turn-coil system up to 130 T (~7 μs) and long-pulse fields up to 50 T (~25 ms). The *c*-axis-oriented YBCO films are grown on a MgO substrate by the laser ablation technique. The thicknesses of the films are about 1000 Å, the transition temperatures (at zero resistance) of the samples are 82.5 K (sample



(a)



(b)

Figure 1. (a) The field dependence of ρ_{ab} measured by a four-terminal DC technique at various temperatures between 40 K and 120 K (90 K, 88 K, 86 K, 84 K, 82 K, 80.4 K, 79 K, 77.5 K, 75 K, 73 K, 71 K, 69 K, 67 K, 65 K, 62.8 K, 60 K, 55 K, 50 K, 45 K, 40 K) under non-destructive long-pulse fields. The magnetic field was applied parallel to the *c*-axis. The applied current direction is perpendicular to the *c*-axis. (b) The temperature dependence of ρ_{ab} at various fixed fields (0, 10, 20, 30, 40, 48 T) deduced from (a).

1) and 83.5 K (samples 2, 3) and the transition width is about 4 K, which corresponds to slightly underdoped samples. The samples were (i) in shapes measuring 30 μm $\times$ 350 μm in the case of sample 2 and (ii) in the form of meander lines 30 (20) μm wide in the case of sample 1 (sample 3) four-contact devices. In all of the experiments we applied currents perpendicular to the *c*-axis and the magnetic field parallel to the *c*-axis. In the single-turn-coil system, up to 130 T [8], we measured the magnetoresistance while minimizing both the sample size and the area of the measurement circuit perpendicular to the magnetic field. In addition, we used a high-frequency digital lock-in technique to improve the signal-to-noise ratio for the AC measurements. The details of the techniques used to measure the DC and AC magnetoresistance in megagauss fields have been described in references [9, 10].

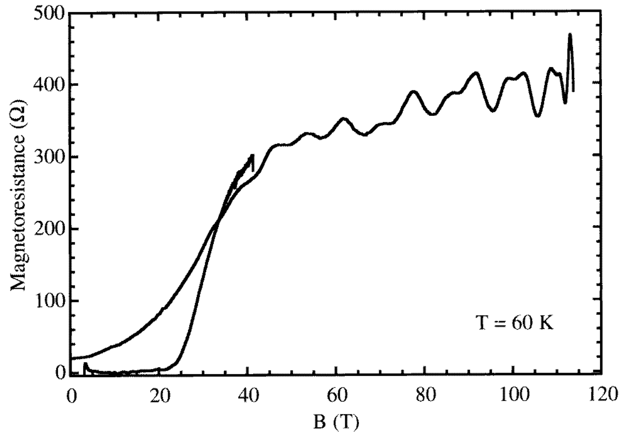


Figure 2. Comparison between the DC magnetoresistance measured under a non-destructive long-pulse field and that measured in a single-turn-coil system. The temperature is 60 K.

We show the magnetoresistance of sample 1 measured at temperatures between 40 K and 90 K in long-pulse fields up to 50 T in figure 1(a) and the temperature dependence of the resistivity at fixed magnetic fields determined from a series of field pulses up to 50 T in figure 1(b). We can suppress the superconductivity only down to about 60 K. It is observed that the zero-resistance state persists with the flux pinned above 50 T below 40 K. A much higher magnetic field is needed to investigate the normal state at lower temperature. So we measured the magnetoresistance using the single-turn-coil system up to 130 T.

In figure 2, we show the magnetoresistance of sample 3 measured in short-pulse fields and that measured in long-pulse fields at 60 K. As shown in figure 2, the former appears at fields lower than the latter. This is because the eddy current proportional to $\mathrm{d}B/\mathrm{d}t$ is very large in short-pulse fields ($\sim$7 μs) and the flux flow rate is field sweep dependent in the case of $\sim\mu$s pulse widths. But they coincide with each other when they are approaching the normal state.

We show the AC and DC magnetoresistance measured at 4.2 K up to 130 T and 115 T in figure 3. It can be seen that the AC magnetoresistance begins to increase rapidly above about 60 T and then tends to saturate at around 120 T. The DC magnetoresistance is qualitatively the same as the AC one and we can see the beginning of the tendency towards saturation at 110 T. So it is apparent that we can suppress the superconductivity in this sample even at 4.2 K ($T/T_c \sim 0.05$).

From the AC and DC magnetoresistance measured in short-pulse fields up to 130 T and long-pulse fields up to 50 T, we determined the upper critical fields H_{c2} at which magnetoresistance tends to saturate. The results of this are shown in figure 4. It is seen that the temperature dependence of H_{c2} is almost linear at higher temperatures near T_c. Using the Werthamer–Helfand–Hohenberg (WHH) theory for type II superconductors [11], the critical field at 0 K was estimated, according to the relation $H_{c2}(0) = 0.69T_c|\mathrm{d}H_{c2}/\mathrm{d}T|$, to be $H_{c2}(0) = 90$–100 T, using the long-pulse data. From figure 4, it is seen that H_{c2} tends to saturate at about 120–130 T towards 0 K. In overdoped $Tl_2Sr_2CuO_y$ and $Bi_2Sr_2CuO_y$, H_{c2} was observed to diverge as T approached 0 K [12, 13]. In our slightly underdoped YBCO, we do not observe such a divergence of H_{c2} down to 4.2 K ($T/T_c \sim 0.05$), though H_{c2} tends to saturate at a slightly higher value than that estimated from the WHH relation near T_c, and we cannot exclude the possibility of the divergence of H_{c2} below 4.2 K. The saturation of H_{c2}

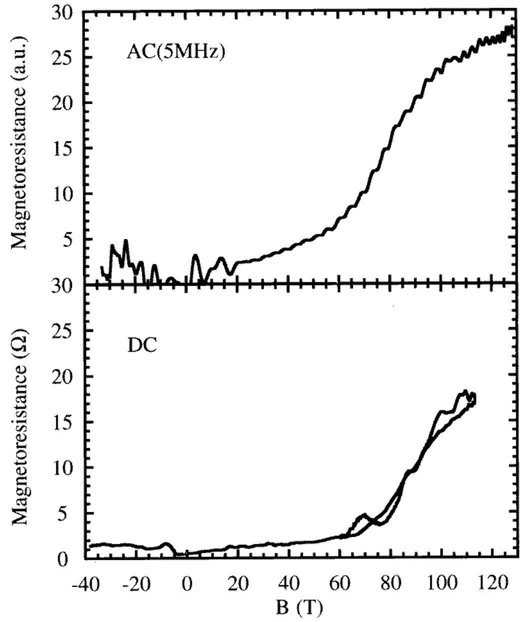


Figure 3. The field dependence of the AC (upper panel) and DC (lower panel) magnetoresistance of sample 2 measured at 4.2 K in a single-turn-coil system. The current and field configuration is the same as in figure 1. The modulation frequency is 5 MHz.

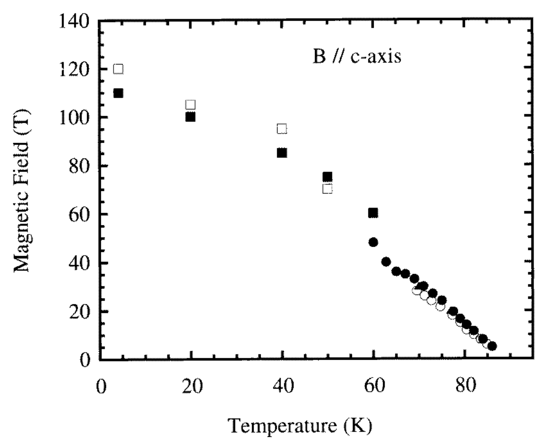


Figure 4. The B–T phase diagram for $\boldsymbol{B}$ parallel to the c-axis. The saturation field (H_{c2}) is indicated by circles and squares. Open squares represent AC measurements and all other symbols represent DC measurements. Open and solid squares represent measurements made in the single-turn-coil system; all other measurements were made in non-destructive long-pulse fields.

in YBCO has also reported from previous transport measurements [14]. The theory which includes the Landau quantization effects at high fields predicts a divergence of H_{c2}, which shows up as precursor to the oscillatory and re-entrant phenomena [15]. The explanation for this may be that the anisotropy of YBCO is much smaller than that of Bi-2201 and Tl-2201,

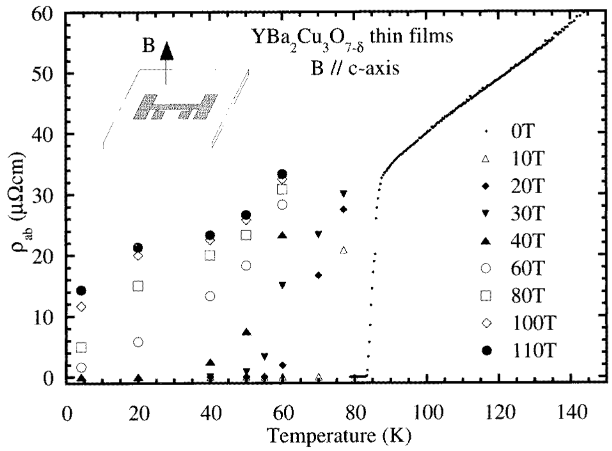


Figure 5. The temperature dependence of ρ_{ab} at various fixed (0, 10, 20, 30, 40, 60, 80, 100, 110 T) fields obtained from the long- and short-pulse magnetic field data for sample 2.

or in other words that three-dimensional behaviour of YBCO, which has been reported in thermodynamical and transport quantities [16], may move this phenomenon to lower temperature. The GL coherence length was calculated to be $\xi_{ab}(0) \sim 16.5$ Å according to the relation $H_{c2} = \Phi_0/2\pi\xi^2$.

Figure 5 presents the temperature dependence of the in-plane resistivity at fixed magnetic fields for sample 2. As regards the resistivity at 110 T, we deduce that it is almost in the normal state from figure 3. The normal-state resistivity decreases with decreasing temperature down to 4.2 K ($T/T_c \sim 0.05$) and tends to saturate to a residual resistivity, though the onset of the superconductivity is visible at 4.2 K. For very underdoped $YBa_2Cu_3O_{7-\delta}$ ($\delta = 0.62$, $T_c = 2$ K), insulating behaviour of the in-plane resistance was reported [17]. However, in our slightly underdoped sample ($T_c = 83.5$ K) we observe a metallic behaviour even at the lowest temperature ($T/T_c \sim 0.05$). Deoxygenating YBCO is known to have increased anisotropy and two dimensionality, and its disorder causes a superconductor–insulator transition because of the anisotropy. If we had observed an insulating behaviour using thin films instead of single crystals, that behaviour might have been caused by the poor quality of the thin films compared with single crystals. However, this is not the case. So the metallic behaviour below T_c is considered to be a universal property. In order to investigate both in-plane and out-of-plane resistivity, we plan to use a-axis-oriented YBCO thin films whose c-axis is aligned in the plane [18].

In summary, we have found that the normal-state in-plane resistivity of slightly underdoped YBCO thin films ($T_c \sim 83.5$ K) remains metallic down to 4.2 K ($T/T_c \sim 0.05$) when the superconductivity is suppressed using short-pulse fields up to 130 T and long-pulse fields up to 50 T. We determined H_{c2} from saturation fields, and find that H_{c2} tends to saturate at around 120 T towards 0 K.

Acknowledgments

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