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Fluctuation conductivity of a *c*-axis-oriented $YBa_2Cu_3O_y$ film prepared by chemical vapor deposition

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The magnetoresistance of a highly *c*-axis-oriented chemical-vapor-deposition film of $YBa_2Cu_3O_y$ was measured in the temperature range $T_c \lesssim T \leq 103$ K for both the $H\|c$ axis and $H\perp c$ axis. The analysis has been done on the basis of the superconducting fluctuation theory for the clean limit, and a good fit has been obtained for the temperature and the magnetic-field dependences of the magnetoconductance in the cases of the $H\|c$ axis and $H\perp c$ axis. The results indicated that all of both orbital and Zeeman effects of the Aslamasov-Larkin and the Maki-Thompson terms contributed to the fluctuation conductivity. The superconducting coherence lengths were estimated to be $\xi_{ab}(0)=11.5$ Å and $\xi_c(0)=3.2$ Å in addition to the phase breaking time of the carrier $\tau_\phi = 8\times 10^{-14}$ sec at 100 K.

In the high-T_c oxides an extremely short coherence length, which originates from high superconducting transition temperature, makes phenomena related with a thermal activation be observable. One of them is a thermally activated behavior in the resistive superconducting transition in an applied magnetic field, which was pointed out in the Bi-Sr-Ca-Cu-O system by Palstra *et al.*[1] According to them the temperature dependence of the resistivity in the low resistance region is described by an Arrhenius law and the estimated activation energy U_0 depends on a magnetic field and an orientation of the crystal to the magnetic field. Afterwards similar behaviors have been reported in the other oxide superconductors of the Y-Ba-Cu-O (Refs. 2 and 3) and Tl-Ba-Ca-Cu-O (Ref. 4) systems. It has been made clear that the broadening of the resistive superconducting transition in a magnetic field is intrinsic property of the high-T_c oxide superconductors and that a vortex state is highly dynamical and complex contrary to conventional superconductors, and the upper critical field H_{c2} cannot be determined by the resistive measurements. So, it is difficult to determine precisely important superconducting parameters, such as coherence length. Another typical phenomenon due to the thermal activation is a superconducting fluctuation. Hikami and Larkin[5] and Maki and Thompson[6] have investigated independently the magnetoconductivity by an orbital effect of the Aslamasov-Larkin (AL) and the Maki-Thompson (MT) terms of the superconducting fluctuation in a layered superconductor weakly coupled along the stucking layer. Furthermore, Aronov, Hikami, and Larkin[7] considered that in two-dimensional-like layered superconductors such as the high-T_c oxides, Zeeman effects must be also taken into account in the magnetoconductance by the superconducting fluctuation. They gave formulas for both the orbital and the Zeeman effects [Aslamasov-Larkin-orbital (ALO), Maki-Thompson-orbital (MTO), Aslamasov-Larkin-Zeeman (ALZ), and Maki-Thompson-Zeeman (MTZ) terms] for a dirty superconductor in the temperature region in which the distribution function of the fluctuation is described by the Gaussian. They have fitted excellently the temperature dependence of the magnetoconductivity $\Delta\sigma_\perp(H)$ and $\Delta\sigma_\|(H)$ of Y-Ba-Cu-O thin film by Matsuda *et al.*[8] for both the $H\perp c$ axis and the $H\|c$ axis, respectively, using their theory for a dirty superconductor. However, the MTZ term was corrected by Thompson[9] later. On the other hand Bieri and Maki[10] and Bieri, Maki, and Thompson[11] gave the ALO, MTO, ALZ, and MTZ terms for a clean superconductor. Studies of the fluctuation conductivity of the Y-Ba-Cu-O system have been reported on bulk single crystals[12,13] on the basis of the theories, in which coherence lengths $\xi_{ab}(0)$ and $\xi_c(0)$, and phase breaking time τ_ϕ were determined. However, it seems that the results of the parameter fitting are still controversial including a question of the contribution of the MTZ term. In this paper we report the results of the magnetoconductivity and its temperature dependence of the *c*-axis oriented Y-Ba-Cu-O film.

Y-Ba-Cu-O sample was prepared by the chemical vapor deposition (CVD) method and was a highly *c*-axis-oriented film with 1.2 μm thickness. Details of the sample preparation have been already reported elsewhere.[14] Magnetic field H was applied parallel and perpendicular to the *c* axis. Current J always flowed on the plane of the film (CuO_2 plane) in the condition of $J\perp H$. Temperature in the magnetic field was controlled within ±20 mK by using a capacitance temperature censor.

In Fig. 1 the temperature dependence of the resistivity in zero magnetic field is shown, where the resistivity is normalized by the *c* factor that arises from an inhomogeneous current flow and an ambiguity of the sample dimension. The value of the *c* factor is 3.5. This large value comes mainly from the ambiguity of the length between voltage terminals, since the length could not be determined precisely for reasons of the sample in our experiments. After the normalization of the resistivity by the *c* factor $d\rho/dT$ is 55 $\mu\Omega$ cm/K. The superconducting transition temperature is $T_c=92.2$ K and its transition width is $\Delta T_c=0.9$ K. *T*-linear resistivity is seen in the high-temperature region and the linearly extrapolated value to 0 K is almost zero. These experimental results indicate high quality of the sample.

Figures 2(a) and 2(b) show the magnetoresistance at the several temperatures above T_c for both the $H\perp c$ axis and the $H \| c$ axis, respectively. In all cases the magnetoresistance shows the relation of

$$\Delta\rho(H)=\rho(H)-\rho(0) \propto H^2$$

in the low-field region, which is a characteristic of the magnetoresistance due to the superconducting fluctuation and its value decreases with increasing temperatures. Furthermore, $\Delta\rho_{\|}(H)$ is much larger than $\Delta\rho_{\perp}(H)$. This corresponds to the suppression of the orbital motion of the carriers for the $H \perp c$ axis as pointed out by the theories and indicates the strong anisotropic three-dimensional or the two-dimensional-like superconducting properties of the Y-Ba-Cu-O crystal.

It is reasonable that because the coherence length is extremely short of the order of 10 Å, Y-Ba-Cu-O is in the clean limit ($l \gg \xi_0, l$: transport mean free path, ξ_0; BCS coherence length). In the following analysis, we adopt the formulas by Bieri, Maki, and Thompson,[11] which are valid for the clean limit and include the correction for the MTZ term by Thompson.[9] The nonlocal effect in the magnetoconductivity is neglected. According to their theory the magnetic field dependence of the ALO, MTO, ALZ, and MTZ terms is proportional to H^2 in the low-field region, while the tendency of the saturation appears at higher magnetic fields in the orbital terms, which is conspicuous just above T_c. This tendency is also seen in the experimental results at $\epsilon=0.0184$ in Fig. 2(a). The Zeeman terms almost hold the H^2 relation in the magnetic field up to 13 T, which is in agreement with our experimental results for the $H \perp c$ axis. Therefore, we use the following equations, which hold in the present magnetic-field region:

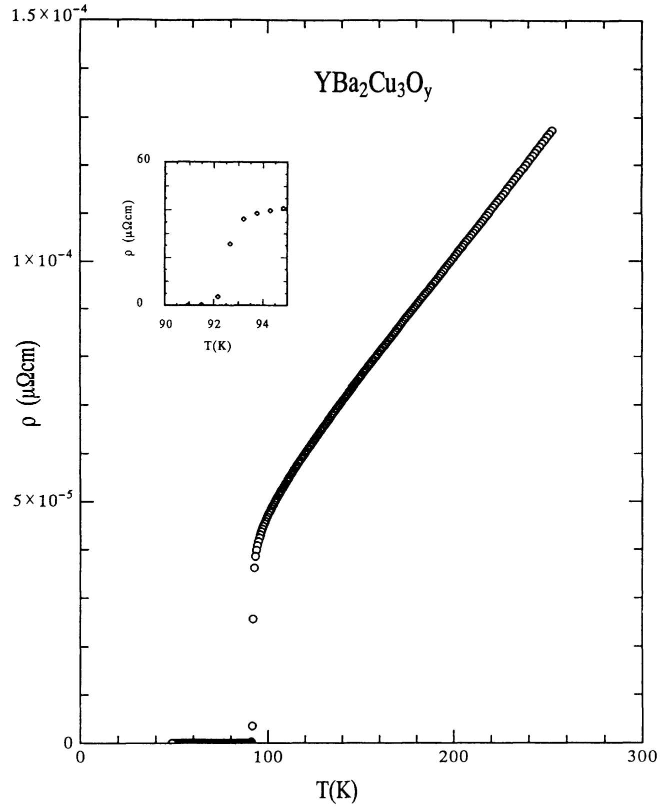

FIG. 1. Temperature dependence of the resistivity of Y-Ba-Cu-O film at zero magnetic field. Inset shows an extended view near T_c.

$$\sigma_{\mathrm{AL}}(0)=\frac{e^2}{16\hbar d}\frac{1}{\epsilon\sqrt{1+2}\alpha}\ , \tag{1}$$

$$\sigma_{\mathrm{MT}}(0)\frac{e^2}{8\hbar d\epsilon(1-\alpha/\delta)}\ln\left[\frac{\delta}{\alpha}\frac{1+\alpha+\sqrt{1+2}\alpha}{\alpha 1+\delta+\sqrt{1+2\delta}}\right]\ , \tag{2}$$

$$\sigma_{\mathrm{ALO}}(H)=\frac{e^2}{8\hbar}\int_0^{2\pi/d}\frac{1}{\epsilon_k}\left[\frac{\epsilon_k}{\hbar}\right]^2\left[\Psi\left[\frac{1}{2}+\frac{\epsilon_k}{2h}\right]-\Psi\left[1+\frac{\epsilon_k}{2h}\right]+\frac{h}{\epsilon_k}\right]\frac{dk}{2\pi}\ , \tag{3}$$

$$\sigma_{\mathrm{MTO}}(H)=\frac{e^2}{8\hbar d\epsilon(\alpha/\delta-1)}\int_0^{2\pi}\left[\Psi\left[\frac{1}{2}+B\right]-\Psi\left[\frac{1}{2}+A\right]\right]\frac{dx}{2\pi}\ , \tag{4}$$

$$\sigma_{\mathrm{ALZ}}(H)\frac{e^2}{16\hbar d}\frac{1}{\epsilon'\sqrt{1+2\alpha'}}\ , \tag{5}$$

$$\sigma_{\mathrm{MTZ}}(H)=\frac{e^2}{8\hbar d\epsilon'(1-\alpha'/\delta)}\ln\left[\frac{\delta}{a'}\frac{1+\alpha'+\sqrt{1+2\alpha'}}{1+\delta+\sqrt{1+2\delta}}\right]\ , \tag{6}$$

where

$$A=\frac{\epsilon}{2h}[1+\alpha(1-\cos x)]\ ,$$

$$B=\frac{\pi\hbar}{16hk_B T\tau_\phi}+\frac{\alpha\epsilon}{2h}(1-\cos x)\ ,$$

$$\epsilon_k=\epsilon[1+\alpha(1-\cos kd)],\quad \epsilon=\ln\left[\frac{T}{T_c}\right]\ ,$$

$$\epsilon'=\ln\frac{T}{T_c(H)}=\epsilon+\mathrm{Re}\left[\Psi\left[\frac{1}{2}+\frac{iw_s}{4\pi k_B T_c}\right]-\Psi\left[\frac{1}{2}\right]\right]\ ,$$

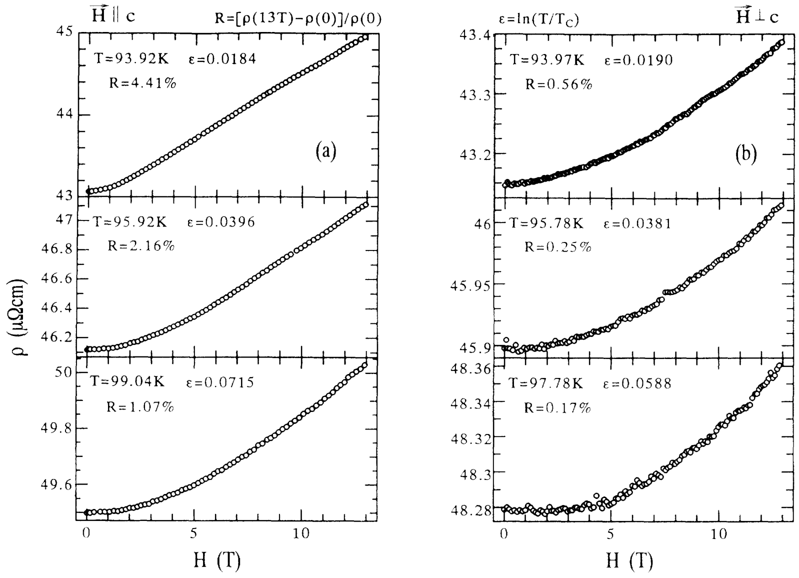

FIG. 2. Magnetoresistance of Y-Ba-Cu-O film for (a) $H \parallel c$ axis and (b) $H \perp c$ axis.

$$\delta = 1.203 \left[\frac{l}{\xi_{ab}(0)} \right] \frac{16 \xi_c^2(0) k_B \tau_\phi}{\pi d^2 \hbar} , \quad \alpha = \frac{2 \xi_c^2(0)}{d^2 \epsilon} ,$$

$$\alpha' = \frac{2 \xi_c^2(0)}{d^2 \epsilon'} , \quad h = \frac{H}{H_{c2}} = \frac{2e \xi_{ab}^2(0) H}{\hbar} , \quad \omega_s = g \mu_B H ,$$

Ψ is the digamma function, and d is an interlayer spacing of 11.68 Å.

Because the orbital motion of the superconducting carriers is strongly suppressed for the $H \perp c$ axis, only the Zeeman terms contribute to the fluctuation conductivity. Magnetoconductivity $\Delta\sigma_{\parallel}(H)$ and $\Delta\sigma_{\perp}(H)$ are given

$$\Delta\sigma_{\parallel}(H) = \Delta\sigma_{\text{ALO}}(H) + \Delta\sigma_{MTO}(H) + \Delta\sigma_{\text{ALZ}}(H) + \Delta\sigma_{\text{MTZ}}(H) \tag{7}$$

and

$$\Delta\sigma_{\perp}(H) = \Delta\sigma_{\text{ALZ}}(H) + \Delta\sigma_{\text{MTZ}}(H) , \tag{8}$$

respectively, where $\Delta\sigma_{\text{ALO}}(H) = \sigma_{\text{ALO}}(H) - \sigma_{\text{ALO}}(0)$, etc. $T_c = 92.2$ K of the middle point of the resistive transition was taken as the mean-field transition temperature. Fitting parameters are $\xi_{ab}(0)$, $\xi_c(0)$, l, and τ_ϕ and the temperature dependence of l and τ_ϕ is assumed to be l, $\tau_\phi \propto T^{-1}$. It should be noted that not only the temperature dependence of the magnetoconductivity but the magnetic-field dependence of one must be fitted by the same parameter values. As shown in Figs. 3, 4(a) and 4(b), a good fitting was obtained for both $\Delta\sigma(H)$ vs ϵ at 13 T and $\Delta\sigma(H)$ vs H. The nonlocal effect discussed in Ref. 11 seems not to be needed to explain the data. We can see a deviation between the experimental and the theoretical results in the $\Delta\sigma_{\parallel}(H)$ vs ϵ at $\epsilon = 0.0161$, which may be due to the interaction between the superconducting fluctuations, since the measured temperature is close to the mean-field transition temperature. The ALO term is dominant near T_c and the MTO term has a large contribution in the high-temperature region. The obtained values of the fitting parameters are summarized in Table I. The results that the transport mean free path is much longer than the coherence length are consistent with the assumption of the clean limit. It is indicated that the values of the coherence length estimated by the fluctuation conductivity are $\xi_{ab}(0) \sim 11$–15 Å and $\xi_c(0) \sim 3$–4 Å and the ratio of them is about $\xi_{ab}(0)/\xi_c(0) \sim 3.7$. The values of $\xi_{ab}(0)$ and $\xi_c(0)$ are almost half of the ones estimated from the H_{c2} determined by the resistance measurements,[15–17] while their ratios are the same. The values obtained by the superconducting fluctuation analysis are rather close to $\xi_{ab}(0) = 3$ Å and $\xi_c(0) = 16$ Å, which were determined from the temperature dependence of H_{c2} in the magnetization measurements.[18] The ratio of l and τ_ϕ is $l/\tau_\phi = 0.9 \times 10^7$ cm/sec and coincides with the Fermi velocity $v_F = (0.7$–$1.6) \times 10^7$ cm/sec, which is evaluated by the in-plane superconducting energy gap $2\Delta_0/k_B T_c = 3.5$–8.[19,20] This implies $\tau_{\text{tr}} \sim \tau_\phi$, where τ_{tr} is

TABLE I. Physical parameters of Y-Ba-Cu-O crystal. l and τ_ϕ are given the values at 100 K. l cannot be determined in Refs. 8 and 12 because the analysis has been done in the dirty limit.

	T_c (K)	ΔT_c (K)	$\xi_{ab}(0)$ (Å)	$\xi_c(0)$ (Å)	τ_ϕ (sec)	l (Å)	Fitting conditions
This work	92.2	0.9	11.5	3.2	8×10^{-14}	70	$\Delta\sigma_{\parallel}, \Delta\sigma_{\perp}$ vs ϵ, $\Delta\sigma_{\parallel}, \Delta\sigma_{\perp}$ vs H
Ref. 8	85.5	1.3	11.2	1.6	1×10^{-13}		$\Delta\sigma_{\parallel}, \Delta\sigma_{\perp}$ vs ϵ, $\Delta\sigma_{\parallel}, \Delta\sigma_{\perp}$ vs H
Ref. 12	90.8	<0.3	15	2.8–3.0	1×10^{-13}		$\Delta\sigma_{\parallel}$ vs H
Ref. 13	92.3	0.3	13.3	3.8	5.4×10^{-14}	108	$\Delta\sigma_{\parallel}, \Delta\sigma_{\perp}$ vs ϵ

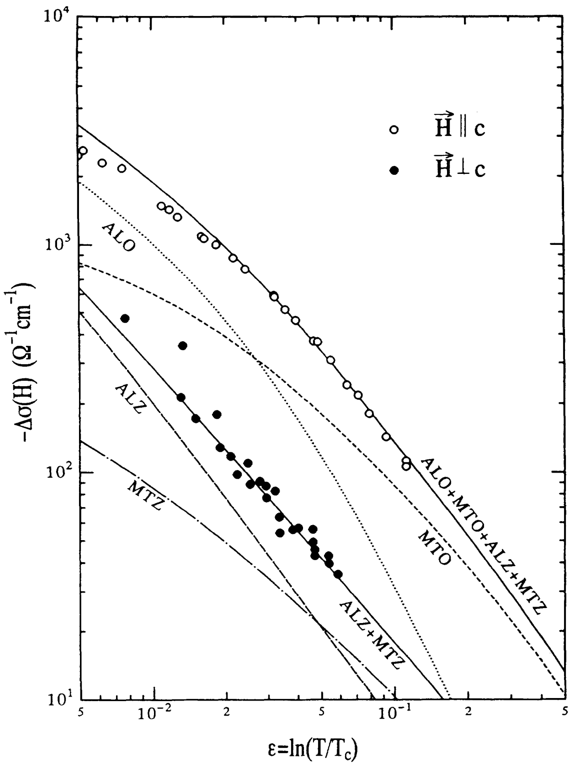

FIG. 3. Temperature dependence of magnetoconductivity at $H = 13$ T. Circles indicate the experimental data and solid line shows the theoretical results. All terms of ALO, MTO, ALZ, and MTZ are also shown the dotted, dashed, dashed, and dotted-dashed lines, respectively.

the transport relaxation time and a scattering that determines the electrical resistance contributes to a pair-breaking process.

In our analysis the MTZ term is necessary to get a good fit, though its contribution is the smallest among the four terms. However, Semba, Ishii, and Matsuda[13] insisted that the temperature dependence of the magnetoresistance could be explained without the MTZ term; that is, the contribution of the MTZ term is negligibly small. In general its contribution tends to be small when τ_ϕ is short. Actually τ_ϕ by Semba, Ishii, and Matsuda[13] is the shortest as shown in Table I. The discrepancy on the parameter fitting seems to come from the anisotropy ratio of $\Delta\sigma_{\parallel}(H)/\Delta\sigma_{\perp}(H)$. The ratio of $H = 1$ T by Semba, Ishii, and Matsuda[13] is approximately 30 at $\epsilon = 0.05$ in contrast to our experimental results $[\Delta\sigma_{\parallel}(H)/\Delta\sigma_{\perp}(H) \sim 13]$ and the results of Matsuda *et al.*[8] $[\Delta\sigma_{\parallel}(H)/\Delta\sigma_{\perp}(H) \sim 7]$ at the same ϵ value. In the films, the *a*-axis-oriented grains might be contained slightly, even in highly *c*-axis-oriented films. In our experiments the current always flows on the plane of the film. So, it is considered that the presence of the *a*-axis-oriented grain does not affect the conductivity because the resistivity along the *c* axis is much larger than that in the *c* plane and the current flows in the *c*-axis-oriented grains only. As mentioned before, the magnetoconductivity ALO and MTO, due to the orbital effect, tend to saturate at high magnetic field of 13 T near T_c, while the MTZ term continues to decrease with the relation of $\Delta\sigma(H) \propto -H^2$ at least up to 13 T, that is, low-field approximation is held at this field. Actually the ratio of $\Delta\sigma_{\parallel}(H)/\Delta\sigma_{\perp}(H)$ decreases with increasing magnetic field in our experiments and is estimated to be ~ 8 at 13 T ($\epsilon = 0.05$) as shown in Fig. 3, because the contribution of the MTZ term becomes relatively larger at high fields than at low fields. This indicates that the contribution of the MTZ term is more apparent in the analysis in which the high-field data are taken into account. Thus it is interpreted that the MTZ term is necessary to have a good fit in our analysis though its contribution is the smallest. However, the discrepancy with respect to the anisotropy ratio of the magnetoconductivity still exists quantitatively between the results of Semba, Ishii, and Matsuda and our results. Another problem such as a scattering in the grain boundary in the film may be included on the contribution of the MTZ term.

In summary, the magnetoconductance observed in the

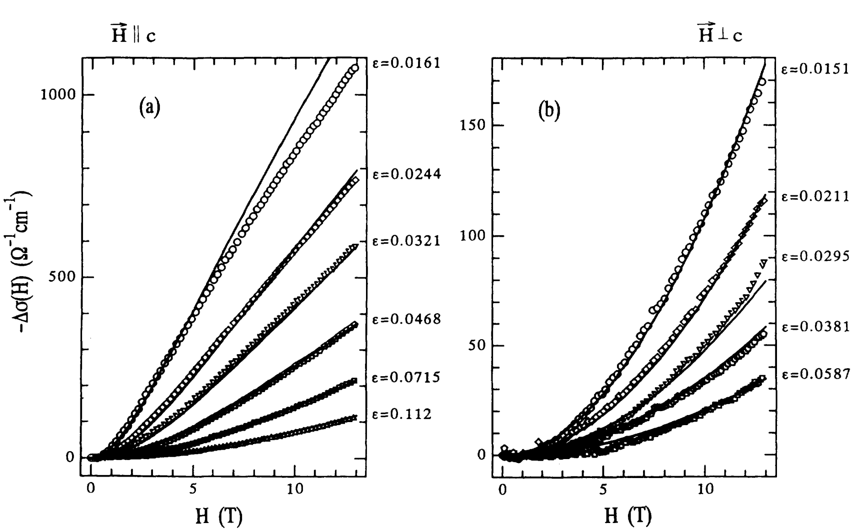

FIG. 4. Magnetoconductivity of Y-Ba-Cu-O film for (a) $H \parallel c$ axis and (b) $H \perp c$ axis. Theoretical results are also shown by solid lines.

c-axis-oriented CBD film of YBa_2Cu_3Oy has been analyzed on the basis of the superconducting fluctuation theory for the clean limit. The results of the analysis indicate that the Maki-Thompson-Zeeman term surely contributes to the fluctuation conductivity in our analysis in which the high-field data up to 13 T have been taken into account, though its contribution is the smallest among the four ALO, MTO, ALZ and MTZ terms.

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