RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 39, NUMBER 7 1 MARCH 1989

Magnetoresistance and thermodynamic fluctuations in single-crystal $YBa_2Cu_3O_y$

Makoto Hikita and Minoru Suzuki
Nippon Telegraph and Telephone Corporation Opto-Electronics Laboratories, Tokai, Ibaraki 319-11, Japan
(Received 29 September 1988)

Magnetoresistance in the *a-b* plane of a single crystal of $YBa_2Cu_3O_y$ has been measured. The field dependence of fluctuation conductivity is evaluated from the magnetoresistance slightly above T_c by considering the Aslamozov-Larkin contribution. The coherence lengths $\xi_{ab}(0)$ and $\xi_c(0)$ are estimated as 13 and 2 Å, respectively. These values are half those obtained from dH_{c2}/dT below T_c. Differences in $\xi(0)$ estimated by different methods are discussed.

The study of anisotropic transport properties in high-T_c 1:2:3 compounds is very important in understanding their intrinsic superconducting characteristics and dimensionality. In an earlier work, the dimensionality of 1:2:3 compounds was determined as three dimensional (3D) from the fluctuation excess conductivity measurements above T_c with sintered samples.[1] Anisotropic coherence lengths $\xi_{ab}(0)$ and $\xi_c(0)$ were estimated from dH_{c2}/dT values in single-crystal 1:2:3 compounds[2-7] with use of the Werthamer-Helfand-Hohenberg (WHH) theory.[8] Although most results supported 3D superconducting behavior, different arguments were also derived from the excess conductivity measurements, which exhibited 2D (Ref. 9) or unconventional temperature-dependent behavior.[10] Recently, Oh *et al.*[11] reported on fluctuation conductivity in $YBa_2Cu_3O_y$ thin films. They claimed that both $\xi_{ab}(0)$ and $\xi_c(0)$ are shorter than those obtained from dH_{c2}/dT near T_c and that the estimated fluctuation conductivity is larger than that derived previously.[1] However, these estimates of excess conductivity are somewhat ambiguous because normal resistivity ρ_n just above T_c was defined by extrapolating resistivity linearly from higher temperature values. Excess conductivity above T_c cannot be determined precisely from the linearly extrapolated ρ_n because $d\rho_n/dT$ is not exactly constant. On the other hand, the magnetoresistance $\Delta\rho$ [$\Delta\rho=\rho(H)-\rho(0)$] above T_c can be obtained precisely from measured values without our knowing ρ_n. Very recently Matsuda, Hirai, and Komiyama[12] studied magnetoresistance above T_c using $YBa_2Cu_3O_y$ sintered samples and obtained results similar to those of Oh *et al.*[11] In the Matsuda, Hirai, and Komiyama study, however, an ambiguous material-dependent parameter called the *C* factor, introduced by Oh *et al.*, was adopted as a sintered sample was used. Thus, the coherence length and dimensionality of 1:2:3 compounds differ significantly depending on estimation methods and experimental results.

This paper evaluates the anisotropic coherence length in single-crystal $YBa_2Cu_3O_y$ in three different ways: from dH_{c2}/dT values, from the concept of a critical region, and from field-dependent fluctuation conductivity. The first two were adopted in earlier works. For the last one, previous works dealt only with temperature-dependent fluctuation conductivity in the absence of a magnetic field. This paper presents a quantitative analysis for field-dependent fluctuation conductivity. The advantage of this method is that the magnetoresistance above T_c in the *a-b* plane is precisely described by the analysis of fluctuation conductivity based on a recent theory developed by Hikami and Larkin.[13] This study focuses on large excess conductivity near T_c, except in the critical region. Since the electron phase-breaking time τ_ϕ has been shown to be small ($\tau_\phi < 10^{-13}$ sec),[14,15] the Aslamazov-Larkin (AL) term is believed to contribute mainly to excess conductivity, and the Maki-Thompson (MT) term is not considered here. Single-crystal $YBa_2Cu_3O_y$ with low resistivity and a sharp superconducting transition is also requisite for the present study. Use of this crystal made a precise determination of T_c possible and enabled a quantitative analysis to be performed.

Single-crystal $YBa_2Cu_3O_y$ was grown by a new procedure with use of only multilayered pellets. This precise growth method has been reported elsewhere.[16] As-grown crystals were annealed at 900 °C for 5 h, cooled to 450 °C, and held at 450 °C for 200 h in oxygen. Resistance was measured by the four-terminal method. Electrical contact was made by use of 25-μm-diam gold wires with conductive silver paste on gold films evaporated on the largest facet of the crystal. A polarized microscope photograph of the single crystal with electrodes for the measurements is shown in Fig. 1. The crystal was determined to be 9.5 μm thick with a scanning electron microscope. Magnetoresistance was measured in a 12-T superconducting

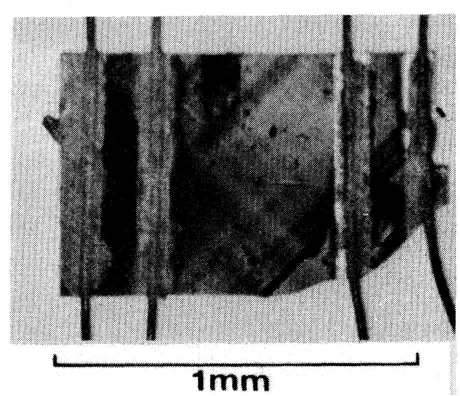

FIG. 1. Polarized microscope photograph of the single-crystal $YBa_2Cu_3O_y$ with electrode for measurement.

magnet. The sample was mounted on a rotating sample holder. The direction of the field parallel or perpendicular to the c axis was determined by the angular dependence of T_c in an 8-T field. Temperature was determined with a calibrated carbon-glass thermometer with detailed corrections for magnetoresistance.

Temperature-dependent resistivity in the a-b plane in a wide temperature range and near T_c is shown in Fig. 2. The rounding of the resistivity curve is observed below 150 K. Above this region, ρ_n is approximately linear in temperature with $d\rho_n/dT = 0.58$ $\mu\Omega$ cm/K. Oh *et al.*[11] proposed that the intrinsic $d\rho_n/dT$ is about 0.5–0.6 $\mu\Omega$ cm/K, where the C factor becomes unity. It should be noted that the sample in this study is in the range where the C factor becomes unity. Therefore, a material-dependent parameter such as the C factor is not needed.

The resistive transition of T_c is sharp within 0.3 K; however, two steplike curves are found as shown in Fig. 2. Therefore, two T_c's, T_{c1} and T_{c2}, are defined at 90.71 and 90.83 K, respectively (Fig. 2). Each T_c can be defined with a precision of less than ± 0.02 K. Although the basic results are unchanged by the difference between the two T_c's, a discussion of the two follows.

The $\rho(H)$-T curves and $T_c(H)$ under various magnetic fields applied perpendicular to the a-b plane are shown in Fig. 3(a). Two steplike curves are clearly observed in the higher-field data. Those are ascribed to T_{c1} (90.71 K) and T_{c2} (90.83 K). Two $T_c(H)$ values, $T_{c1}(H)$ and $T_{c2}(H)$, are defined as shown in Fig. 3. The dH_{c2}/dT values for T_{c1} and T_{c2} in Fig. 3(a) obtained from the data around 70–80 K are 0.72 and 0.79 T/K, respectively. The $\rho(H)$-T curves and $T_c(H)$ under the field applied parallel to the a-b plane are shown in Fig. 3(b). The dH_{c2}/dT values for T_{c1} and T_{c2} in Fig. 3(b) are obtained from the data around 88–89 K are 2.7 and 3.6 T/K, respectively. With the assumption of the WHH theory,[8] $\xi_{ab}(0)$ and $\xi_c(0)$ are estimated as 26–27 and 5.5–7 Å, respectively.[17] These values are similar to those previously reported for single crystals.[2–6]

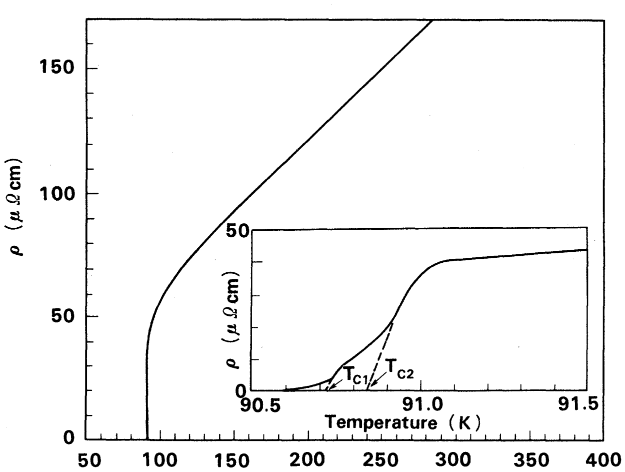

FIG. 2. Temperature-dependent resistivity in the a-b plane. Inset: Expansion of the temperature region in 1.0 K around T_c.

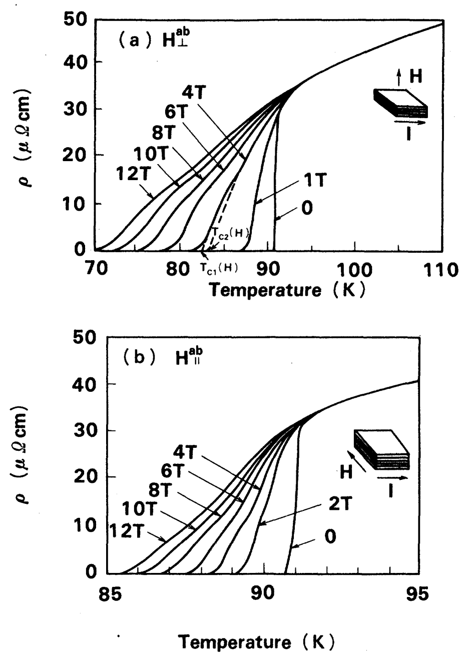

FIG. 3. Temperature dependence of resistivity in various fields (a) perpendicular and (b) parallel to the a-b plane. $T_{c1}(H)$ and $T_{c2}(H)$ are defined in (a).

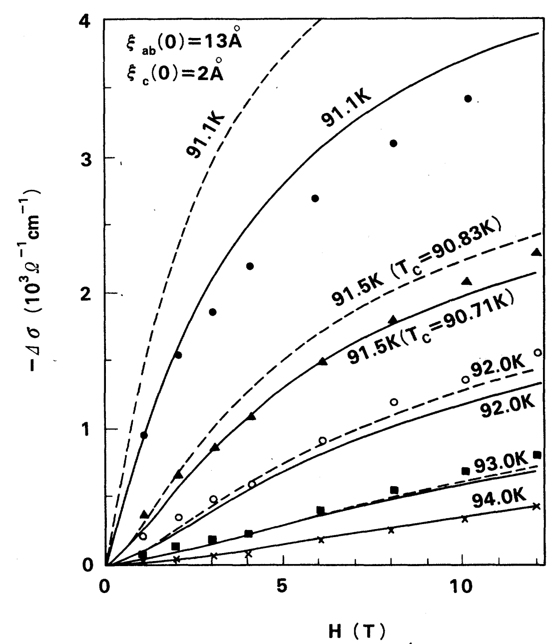

FIG. 4. Field H dependence of the magnetoconductivity $\Delta\sigma$ $[=\sigma(H)-\sigma(0)]$ on various temperatures above T_c. Measurement data: ●, 91.1 K; ▲, 91.5 K; ○, 92.0 K; ■, 93.0 K; and ×, 94.0 K. The solid lines indicate the calculated values with the parameters of both $\xi_{ab}(0) = 13$ Å and $\xi_c(0) = 2$ Å in Eq. (1) for the cases of T_c at 90.71 K. The dashed lines indicate the cases at $T_c = 90.83$ K. Both calculated values are approximately the same at 94.0 K.

Figure 4 shows magnetoconductivity $\Delta\sigma$ in the *a-b* plane above T_c obtained from the data in Fig. 3(a), where $\Delta\sigma=\sigma(H)-\sigma(0)=1/\rho(H)-1/\rho(0)$. Hikami and Larkin[13] derived the analytical form for the magnetoconductance of the AL and MT terms for layered superconductors where the 2D superconductor layers are weakly coupled. The AL term is described by the following equation:

$$\Delta\sigma_{\mathrm{AL}}=\sigma_{\mathrm{AL}}(H)-\sigma_{\mathrm{AL}}(0)=\frac{e^2}{8\hbar}\int_0^{2\pi/d}\frac{1}{\epsilon_k}\left[\frac{\epsilon_k}{h}\right]^2\left[\psi\left(\frac{1}{2}+\frac{\epsilon_k}{2h}\right)-\psi\left(1+\frac{\epsilon_k}{2h}\right)+\frac{h}{\epsilon_k}\right]\frac{dk}{2\pi}-\frac{e^2}{16\hbar}\int_0^{2\pi/d}\frac{1}{\epsilon_k}\frac{dk}{2\pi}, \tag{1}$$

where

$$h=\ln\frac{T_c(0)}{T_c(H)}=\frac{2|e|}{\hbar c}\xi_{ab}^2(0)H,$$

$$\epsilon_k=\epsilon[1+\alpha(1-\cos k_{\parallel}d)],$$

and where $\alpha=2\xi_c^2(T)/d^2=2\xi_c^2(0)/d^2\epsilon$, $\epsilon=\ln(T/T_c)\approx(T-T_c)/T_c$, d is the distance between conducting layers, H is an applied field, ψ is the digamma function, and $k_{\parallel}$ is the momentum parallel to the magnetic field. For $H=0$, the $\sigma_{\mathrm{AL}}(0)$ is given by

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

as proposed by Lawrence and Doniach.[18] When $\alpha\gg1$, Eq. (1) leads to a 3D result, and a 2D case is obtained when $\alpha\ll1$, i.e., Eq. (1) expresses a crossover from 2D to 3D. If Eq. (1) is applied under a temperature range below the crossover point, the anisotropic 3D-like behavior of the AL term mainly manifests itself irrespective of the intrinsic dimensionality. Thus, the formula becomes a good description for both quasi-2D and anisotropic 3D superconductors. Therefore, Eq. (1) is adopted for the AL term to evaluate $\Delta\sigma$.

The fluctuation analysis was performed at five points at temperatures near T_c, from $t=1.003$ to 1.036 ($T=91.1$, 91.5, 92.0, 93.0, and 94.0 K), where $t=T/T_c$.

First, we discuss the origin of the magnetoresistance. Since Eq. (1) was derived from the time-dependent Ginzburg-Landau equation, applying it to the critical region may not give a good approximation. In the present case, the critical region ΔT_{cr} is roughly estimated to be less than 1 K.[19] Therefore, the data at each temperature, except 91.1 K in the present estimation, is considered to be outside the critical region, while the data points at 91.5 K are difficult to determine. Conversely, the magnetoresistance above 95 K is smaller than 1% of the resistance. If magnetoresistance arising from an origin other than fluctuation conductivity coexists, the analysis becomes very difficult and complex. A lot of theories for high-T_c mechanisms suggest that spin fluctuation and magnetic ordering are important. There may be a small amount of magnetoresistance arising from spin fluctuations or other related mechanisms. However, the magnetoresistance in the temperature region for the present experiment can be believed to be mainly attributable to thermodynamic fluctuations because no reason is known for such a large magnetoresistance near T_c. Because of this, the temperature region in the present experiments leads to a good evaluation of fluctuation conductivity.

The calculated $\Delta\sigma_{\mathrm{AL}}(T,H)$ is shown in Fig. 4 for both T_{c1} and T_{c2}, where d is assumed as the c-axis lattice constant of 11.7 Å. The parameters α and h are adjusted so that the $\Delta\sigma_{\mathrm{AL}}$ curves fit the experimental data at each fixed temperature. Through this procedure, the $\xi_{ab}(0)$ of 13 Å and $\xi_c(0)$ of 2 Å are obtained from the best fit shown in Fig. 4.[20] These values are only one-half those obtained from dH_{c2}/dT. An attempt was also made to obtain $\Delta\sigma$ from Fig. 3(b), but it was too small for precise values to be realized. This fact qualitatively supports the results that the coherence length is significantly anisotropic.[21] It is interesting to note that an average value of $\xi_{\mathrm{av}}(0)$ of 7 ± 0.5 Å has been estimated from the specific-heat fluctuation measurement by Inderhees *et al.*[22] This is in good agreement with the present results when the relation of $\xi_{\mathrm{av}}^3(0)=\xi_x(0)\xi_y(0)\xi_z(0)$ is assumed for the anisotropic 3D case proposed by Bulaevskii, Ginzburg, and Sobyanin.[23] It should also be noted that the results[11,12] obtained by the use of the factor C introduced by Oh *et al.*[15] agree closely with our results. If the idea of factor C is accepted, the excess conductivity estimated in the sintered samples may change. At present, the origin of factor C is ambiguous, and future study is need to clarify it.

If $\xi_{ab}(0)$ and $\xi_c(0)$, as obtained above, are used to estimate $H_{c2}(0)$ from the relations $H_{c2}^{ab\perp}(0)=\Phi_0/2\pi\xi_{ab}^2(0)$ and $H_{c2}^{ab\parallel}(0)=\Phi_0/2\pi\xi_{ab}(0)\xi_c(0)$, $H_{c2}^{ab\perp}(0)$ and $H_{c2}^{ab\parallel}(0)$ become 200 and 1200 T, respectively. These values are surprisingly large compared with those estimated from dH_{c2}/dt. One of the most important causes of the differences of $\xi(0)$ and $H_{c2}(0)$ between the different estimation methods can be ascribed to flux creep in the H_{c2} measurements below T_c. Yeshurun and Malozemoff[24] pointed out that giant flux creep in $YBa_2Cu_3O_y$ can contribute to curvature of $\rho(H)$ near $T_c(H)$. Indeed, the magnetoresistance in the *a-b* plane of a single-crystal $EuBa_2Cu_3O_y$ appears above 25 T at 4.2 K (Ref. 7) in a pulsed high magnetic field. If the discrepancy of $H_{c2}(0)$ values obtained by different methods is caused by flux creep, giant flux creep must be accepted.

We also attempted to estimate $\xi(0)$ by another method, based on the idea of critical fluctuation below T_c proposed by Oh *et al.*[11] If critical fluctuation occurs, $H_{c2}(T)$ is described by the relation[25]

$$H_{c2}(T)=[\Phi_0/2\pi\xi(0)^2]\{[T_c(0)-T_c(H)]/T_c(0)\}^{2\nu}.$$

Log-log scale data for $H_{c2}(T)$ perpendicular and parallel to the *a-b* plane versus $1-t$ are shown in Fig. 5. From these plots, 2ν of 1.2 and $\xi_{ab}(0)=20$ Å from $H_{c2}^{ab\perp}(T)$, and 2ν of 1.25–1.35 and $\xi_c(0)=2$–3.5 Å from $H_{c2}^{ab\parallel}(T)$ are obtained. Calculation of the AL term with use of $\xi_{ab}(0)=20$ Å is attempted, but the curve does not fit the experimental data well. The calculated $\Delta\sigma(H)$-H curve saturates at a higher field than with the experimental

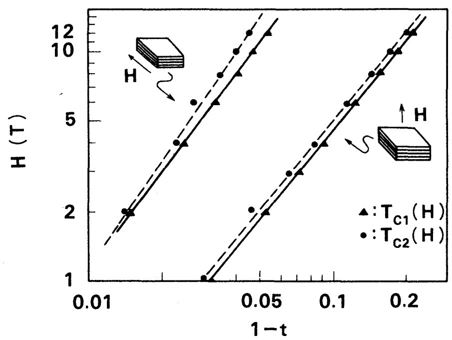

FIG. 5. Log-log plot with $T_{c1}(H)$ and $T_{c2}(H)$ vs applied field parallel and perpendicular to the *a*-*b* plane. The solid and dashed lines are for $T_{c1}(H)$ and $T_{c2}(H)$, respectively. $t=T/T_c$.

data. The substantial deviation of 2ν from the mean-field value ($2\nu=1$) is thought to be explained by the combined effects of dimensional crossover and flux creep.

Hikami[26] recently predicted that the crossover region from 3D to 2D shifts by the magnetic field is due to the suppression of 3D superconductivity, and that 2ν would deviate from the mean-field value.[27] According to this prediction, dimensional crossover below T_c is expected when $\xi_c(0)\approx 2$ Å. This effect is also explained by the flux creep model proposed by Yeshurun and Malozemoff.[24] Both these effects seem to play an important role in the deviation of 2ν from the mean-field value. Furthermore, two factors can contribute independently to 2ν values. Thus, direct application of the expression for ξ in the critical region does not necessarily lead to true coherence length.

In conclusion, fluctuation conductivity is estimated from magnetoresistance measurements in the *a*-*b* plane with high quality single-crystal $YBa_2Cu_3O_y$. The data's good agreement with the AL contribution leads to the much shorter coherence lengths of $\xi_{ab}(0)=13$ Å and $\xi_c(0)=2$ Å than those evaluated by dH_{c2}/dT. In this study, we claim that 1:2:3 compounds exhibit the following unconventional behavior: If coherent length is recognized to be short, anomalous large H_{c2} and giant flux flow must be accepted; if coherent length is longer than the values estimated from fluctuation conductivity, we must accept the existence of large strange magnetoresistance above T_c.

The authors are extremely grateful to S. Hikami and S. Komiyama for copies of work prior to publication, and discussions. They also would like to thank Y. Katayama, A. Yamaji, and T. Murakami for their continuous support and encouragement, T. Konaka for growing the crystals, and Y. Tajima for sample preparations.

[1]P. P. Freitas, C. C. Tsuei, and T. S. Plaskett, Phys. Rev. B **36**, 833 (1987).

[2]T. K. Worthington, W. J. Gallagher, and T. R. Dinger, Phys. Rev. Lett. **59**, 1160 (1987).

[3]Y. Iye, T. Tamegai, H. Takeya, and H. Takei, Jpn. J. Appl. Phys. Pt. 2 **26**, L1057 (1987).

[4]M. Hikita, Y. Tajima, A. Katsui, Y. Hidaka, T. Iwata, and S. Tsurumi, Phys. Rev. B **36**, 7199 (1987).

[5]J. S. Moodera, R. Meservey, J. E. Tkaczyk, C. X. Hao, G. A. Gibson, and P. M. Tedrow, Phys. Rev. B **37**, 619 (1988).

[6]M. Oda, Y. Hidaka, M. Suzuki, and T. Murakami, Phys. Rev. B **38**, 252 (1988).

[7]Y. Tajima, M. Hikita, T. Ishii, H. Fuke, K. Sugiyama, M. Date, A. Yamagishi, A. Katsui, Y. Hidaka, T. Iwata, and S. Tsurumi, Phys. Rev. B **37**, 7956 (1988).

[8]N. R. Werthamer, E. Helfand, and P. C. Hohenberg, Phys. Rev. **147**, 295 (1966).

[9]M. Ausloos and Ch. Laurent, Phys. Rev. B **37**, 611 (1988).

[10]N. P. Ong, Z. Z. Wang, S. Hagen, T. W. Jing, J. Clayhold, and J. Horvath, Physica C **153–155**, 1072 (1988).

[11]B. Oh, K. Char, A. D. Kent, M. Naito, M. R. Beasley, T. H. Geballe, R. H. Hammond, A. Kapitulnik, and J. M. Graybeal, Phys. Rev. B **37**, 7861 (1988).

[12]Y. Matsuda, T. Hirai, and S. Komiyama, Solid State Commun. **68**, 103 (1988).

[13]S. Hikami and A. I. Larkin, Mod. Phys. Lett. B **2**, 693 (1988).

[14]Z. Schlesinger, R. T. Collins, D. L. Kaiser, and F. Holtzberg, Phys. Rev. Lett. **59**, 1958 (1987).

[15]M. Gurvich and A. T. Fiory, Phys. Rev. Lett. **59**, 1337 (1987).

[16]T. Konaka, I. Sankawa, M. Sato, and M. Hikita, J. Cryst. Growth **91**, 278 (1988).

[17]In this estimation, $H_{c2}=0.69T_c$ (dH_{c2}/dT) is used because it was very often applied in early works. If the linear extrapolation form $H_{c2}=T_c$ (dH_{c2}/dT) is assumed, slightly smaller values, where $\xi_{ab}(0)=21$–22 Å and $\xi_c(0)=4.5$–6 Å, result. However, this does not really affect the conclusions.

[18]W. E. Lawrence and S. Doniach, in *Proceedings of the Twelfth International Conference on Low Temperature Physics, Kyoto, Japan, 1970,* edited by E. Kanda (Keigaku, Tokyo, 1971), p. 361.

[19]C. J. Lobb, Phys. Rev. B **36**, 3930 (1987).

[20]Although α is a directly obtained value, this estimation is a little ambiguous for $\xi_c(0)$ because d cannot be determined precisely. $YBa_2Cu_3O_y$ has two CuO_2 sheets in each unit cell. There are two different distances between CuO_2 sheets sandwiching Y or Ba ions. If d is assumed to be the longer distance (8.3 Å) between CuO_2 layers where Ba ions are sandwiched, $\xi_c(0)$ is 1.5 Å. If d is assumed to be the distance of one-half of a unit cell, then $\xi_c(0)$ is 1 Å. However, conclusions are not affected in any substantial way by this.

[21]S. Hikami (private communication).

[22]S. E. Inderhees, M. B. Salamon, N. Goldenfeld, J. P. Rice, B. G. Pazol, D. M. Ginsberg, J. Z. Liu, and G. W. Crabtree, Phys. Rev. Lett. **60**, 1178 (1988).

[23]L. N. Bulaevskii, V. L. Ginzburg, and A. A. Sobyanin, Physica C **152**, 378 (1988).

[24]Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988); A. P. Malozemoff, in *Proceedings of the First International Symposium on Superconductivity, Nagoya, Japan, 1988,* edited by K. Kitazawa (Springer-Verlag, Tokyo, in press).

[25]A. Kapitulnik, M. R. Beasley, C. Castellani, and C. Di Castro, Phys. Rev. B **37**, 537 (1988).

[26]S. Hikami (unpublished).

[27]S. Hikami and T. Tsuneto, Prog. Theor. Phys. **63**, 387 (1980).

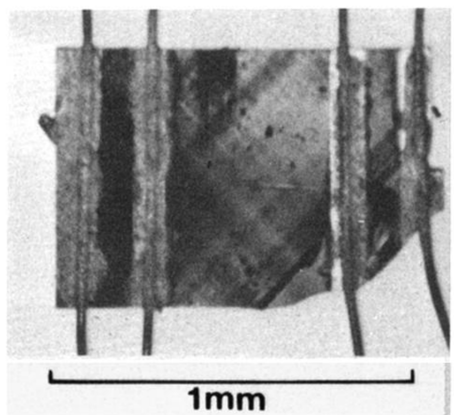

FIG. 1. Polarized microscope photograph of the single-crystal $YBa_2Cu_3O_y$ with electrode for measurement.