Superconducting fluctuation probed by in-plane and out-of-plane conductivities in $Tl_2Ba_2CaCuO_{8+y}$ single crystals

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(Received 10 November 2002; published 4 April 2003)

Extensive measurements of the in-plane and the out-of-plane zero field resistivities $[\rho_{ab}(T,0),\ \rho_c(T,0)]$ and the magnetoresistivities $[\rho_{ab}(T,H),\ \rho_c(T,H)]$ of high-quality $Tl_2Ba_2CaCu_2O_{8+y}$ single crystals were carried out. The obtained zero field fluctuation conductivities $[\Delta\sigma_{ab}(T,0),\ \Delta\sigma_c(T,0)]$ and fluctuation-induced magnetoconductivities $[\Delta\sigma_{ab}(T,H)$ and $\Delta\sigma_c(T,H)]$ were analyzed based on the theory of thermal fluctuations of the superconducting order parameters, originated from fluctuations of the quasiparticle density of states as well as the Aslamazov-Lakin and Maki-Thompson contributions. We observed that $\Delta\sigma_{ab}(T,H)$ and the sign change in $\Delta\sigma_c(T,H)$ near T_c could be described adequately only if the density of states contribution was included. The important physical parameters, such as the coherence length (ξ), the in-plane scattering time (τ), and the hopping integral (J), obtained during these analyses are compared with the corresponding parameters for other high-T_c materials.

DOI: 10.1103/PhysRevB.67.144502 PACS number(s): 74.25.Fy, 74.40.+k, 74.72.−h

I. INTRODUCTION

The most unique characteristics in high-T_c superconductors (HTSC's) are their unconventional normal-state properties. Especially, the temperature dependences of both the in-plane (ρ_{ab}) and the c-axis resistivities (ρ_c) are known to behave differently, even when near the optimally doped state; ρ_{ab} is metallic, and ρ_c is semiconducting near the transition temperature.[1–5] The simultaneous appearance of a metallic ρ_{ab} and a semiconducting ρ_c over a wide range of doping concentrations seems to be not well explained within the framework of a Landau-Fermi liquid. Anomalous behaviors in normal-state transport are also observed in the magnetoresistance (MR). In the ab plane, MR has positive values; $\Delta\rho_{ab}(H)/\rho_{ab}(0)>0$ and violates Kohler's rule.[6] However, in the c direction, it has negative values; $\Delta\rho_c(H)/\rho_c(0)<0$ well above T_c.[3] Several attempts based on the theory of a modified Landau-Fermi liquid, such as renormalized interlayer hopping,[7] interlayer scattering,[8,9] phonon-assisted tunneling,[10] superconducting fluctuation theories,[11] and a theory that considers the temperature-dependent suppression of the density of states at Fermi level,[12] have been made to explain these anomalous behaviors. Theories that give non-Fermi-liquid behaviors also exist: the resonating valence bond theory (RVB) and the in-plane quasiparticle confinement theory.[13–15]

The fluctuation conductivity, which is part of the anomalous normal state transport, is not negligible in HTSC's. This conductivity is highly enhanced in HTSC's because of the high transition temperature, the short coherence length, and the layered structure of these materials. The fluctuation conductivity was investigated theoretically in the mean-field region by many authors.[11,16–21] Most of them claimed that the dominant contribution to the in-plane fluctuation conductivity $\Delta\sigma_{ab}(T,0)$ came from the Aslamazov-Lakin (AL) process[16] and that a minor correction came from the Maki-Thompson (MT) process.[17,18] The AL process takes into account the electric-field acceleration of the short-lived superconducting pairs that form above T_c, and the MT process results from the quasiparticle contributions to the conductivity during the breaking and reforming of Cooper pairs.

Several reports have interpreted both the in-plane fluctuation conductivity $\Delta\sigma_{ab}(T,0)$ and the fluctuation-induced magnetoconductivity $\Delta\sigma_{ab}(T,H)$ based on only the AL process or on both the AL and the MT processes.[22–25] For instance, in Ref. 26 the experimental results for $\Delta\sigma_{ab}(T,0)$, $\Delta\sigma_{ab}(T,H)$, and the diamagnetism of $Bi_2Sr_2CaCu_2O_8$ single crystals were analyzed by using only the AL theory. In that analysis, the AL theory was modified by considering n superconducting layers per unit cell coupled through various coupling strengths γ_j. The authors insisted that their data were well explained within this modified AL theory but the contributions of the AL term became twice larger after the effective number of fluctuating layers was introduced, which is based on the assumption of equal coupling strength $(\gamma_1\approx\gamma_2)$. However, this assumption is unreasonable for this system because the distance from one CuO_2 plane to the closest one is much smaller than the distance to the next closest plane. Moreover, although $\Delta\sigma_{ab}(T,0)$ could be explained by using this modified AL theory, $\Delta\sigma_{ab}(T,H)$ could not without introducing oxygen inhomogeneities.

Even the combined effect of the AL and the MT processes is insufficient to explain the sign change of the zero-field out-of-plane fluctuation conductivity and fluctuation-induced magnetoconductivity $[\Delta\sigma_c(T,0)$ and $\Delta\sigma_c(T,H)$, respectively$]$ at both underdoped and optimally doped states.[27–31] This behavior can be understood only when the contribution of fluctuations in the quasiparticle density of states (FDOS) is taken into account.[11,21] Since this process reduces the total number of quasiparticles, this contribution is negative in sign. In c-axis charge transport at high temperatures, the FDOS is a dominant process while at low temperatures, the AL contribution is larger than the FDOS contribution. Therefore, competition between the AL and the FDOS processes results in a change in sign. The presence of the FDOS contribution in out-of-plane conductivity requires this contribution to be included even in the in-plane conductivity. In this sense, the validity of previous results obtained without the FDOS contribution should be carefully reexamined. Indeed, in later studies on $\Delta\sigma_{ab}(T,H)$ in $YBa_2Cu_3O_{7-\delta}$, the FDOS contribution was treated as an important one.[32–34]

Among HTSC's, $Tl_2Ba_2CaCu_2O_{8+y}$ (Tl2212) is very attractive because the structure of Tl2212 is typical for bilayered HTSC's. Even though it is an isostructure to $Bi_2Sr_2CaCu_2O_8$, the superlattice of the repeated unit, with lattice constant in the a and b directions of about $3.8a$ and $4.7b$, respectively,[35,36] which $Bi_2Sr_2CaCu_2O_8$ has, does not exist in Tl2212. The absence of superlattice and strong fluctuations in the in-plane and the out-of-plane resistivities due to the highly anisotropic nature of Tl2212 make Tl2212 ideal for studying the fluctuation conductivity. However, due to its toxicity and high vapor pressure, no serious attempts have been made to synthesize the high-quality single crystals, thus preventing extensive study of the fluctuation conductivity and the fluctuation-induced magnetoconductivity in this material.

To the best of our knowledge, only one measurement of $\Delta\sigma_{ab}(T,0)$ in a Tl2212 single crystal exists.[37,38] They found that ρ_{ab}(T) showed a downward curvature in the normal state and no peak appeared for $\rho_c(T)$, which might be due to the inhomogeneous distribution of oxygen inside the sample. Nevertheless, the authors assumed a background linear with temperature for $\Delta\sigma_{ab}(T,0)$. This assumption can hardly be justified except in the range of optimal doping. Moreover, only a qualitative agreement was found between their data and the AL contribution, and the necessity of other indirect contributions was not justified. A study of $\Delta\sigma_{ab}(T,H)$ in a Tl2212 thin film also exists. In the thin-film sample, however, the extrinsic property of the grain boundary might influence the charge transport.

In this research, to clarify the effects of different contributions to the zero-field fluctuation conductivity $\Delta\sigma(T,0)$ and to the fluctuation induced magnetoconductivity $\Delta\sigma(T,H)$ along the ab plane and the c axis in the mean-field region, we measured the in-plane and the out-of-plane resistivities of high-quality single crystals of Tl2212 with $H\|c$ up to 5 T. The $\Delta\sigma_{ab}(T,H)$ and the $\Delta\sigma_c(T,H)$ were obtained for different samples, and these data were analyzed based on the theory of Dorin *et al.* in the weak-field limit[11] that included the AL, MT, and FDOS processes. We found that the FDOS contribution was essential along with the other contributions to explain the experimental results for both the directions. To obtain the $\Delta\sigma(T,0)$, one should subtract the background resistivity obtained by fitting the normal-state resistivity. However, this procedure is nontrivial, especially for ρ_c. Thus, $\Delta\sigma(T,H)$ which is independent of a background estimation was analyzed first and then $\Delta\sigma(T,0)$ was investigated based on the results of $\Delta\sigma(T,H)$. Through this procedure, the validity of the normal-state background could be confirmed.

II. EXPERIMENT

The measurements of $\rho_{ab}(T,H)$ and $\rho_c(T,H)$ were carried out on single crystals of Tl2212 grown by using the flux method. Single crystals of Tl2212 were grown from mixtures of Tl_2O_3 and a precursor $Ba_2CaCu_2O_x$. The details of the growth procedure are described elsewhere.[39–41] Crystals with typical dimensions of $0.5\times0.5\times0.05$ mm^3 were selected and annealed in oxygen for 48 h at a temperature of 400 °C. After the annealing process, crystals were examined using an optical microscope. The crystals showed metallic shining surfaces. Some of the crystals were further characterized by using x-ray diffraction with four circle goniometers and by using low-field magnetization. The x-ray diffraction patterns showed very sharp (00l) peaks characteristic of the 2212 structure with $c\sim29.3$ Å.[41] The low-field magnetization data showed the onset transition temperature of 106 K, as shown in the upper inset of Fig. 1(a). The good quality of these samples was also confirmed by extensive reversible and irreversible magnetization studies.[39–41] In the reversible magnetization study, the nonlocal effect in the relation between the current density and vector field was revealed to be important, and in the irreversible magnetization studies, various vortex phases, and their dynamic properties were identified.

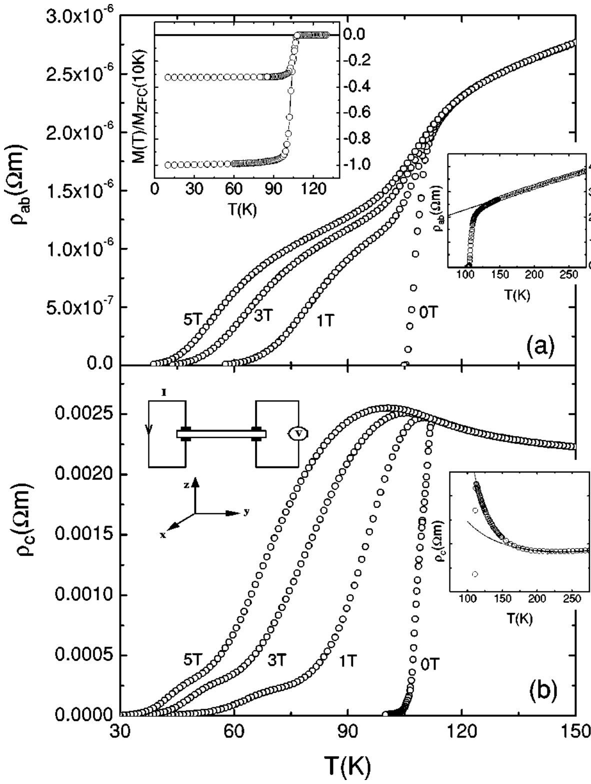

FIG. 1. (a) Temperature dependence of the in-plane resistivity $\rho_{ab}(T)$ for various values of the external magnetic field. The upper inset shows the low-field magnetization of the same crystal and the lower inset shows the zero field measured in-plane resistivity along with a linearly fitted curve (solid line) at the normal state. (b) Temperature dependence of the out-of-plane resistivity $\rho_c(T)$ for various values of the external magnetic field. The inset at the lower panel (right side) presents the zero field measured c-axis resistivity along with the fitted curves; the solid line by using the relation $A+BT+C/T$ and the dashed line by using the relation $A+BT+C/T\exp(\Delta/T)$. The another inset (top corner) presents the contact configuration for ρ_c measurement.

The resistivity was measured in the four-probe configuration for $\rho_{ab}(T,H)$ and in the direct cross configuration for $\rho_c(T,H)$ as shown in the inset of Fig. 1(b) (top corner). In this cross configuration, when the current and the voltage pads are close to each other, the very large anisotropy ($\rho_c/\rho_{ab} \approx 10^3$–$10^4$) of Tl2212 gave reliable values for ρ_c because the planes perpendicular to the current flow could be regarded as equipotential surfaces.[29,42] The contact pads were made by evaporating gold and then annealed in air for 30 min to reduce the contact resistance. The gold wires were attached to the contact pads by using silver epoxy (EPOTEK P1011), and the contact resistance was found to be less than 2 Ω. A current $I=100\mu$A was passed through the current leads for both types of measurements. The temperature dependences of ρ_{ab} and ρ_c with different magnetic fields applied parallel to the c axis for two different samples are shown in Fig. 1. Here, the magnetic fields were applied by using a MagLab2000 (Oxford) superconducting system. $\rho_{ab}(T,0)$ follows a linear behavior in temperature well above transition temperature. This behavior is characteristics of optimally doped samples. The application of a magnetic field reduced the critical transition temperature T_c and broadened the transition width for both the in-plane and the out-of-plane resistivities. The main mechanisms for broadening this transition width along the ab plane, flux flow motion and thermally activated flux-flow have been studied extensively.[43] Though different mechanism are suggested to explain the broadening of the transition width along the c axis,[44,45] but it is still unclear. The c-axis peak near the transition temperature was enhanced by increasing the magnetic fields, and the peak position was shifted towards lower temperatures. This behavior was also observed in $Bi_2Sr_2CaCu_2O_8$ single crystals,[44,46] in Tl2212 single crystals,[42,47] and in oxygen-reduced $YBa_2Cu_3O_{7-\delta}$ single crystal.[3] However, in optimally doped $YBa_2Cu_3O_{7-\delta}$, the out-of-plane resistivity shows a metallic behavior.[27]

III. RESULTS AND DISCUSSION

If $\Delta\sigma(T,0)$ is to be analyzed, the normal-state background resistivity should be subtracted. Since $\rho_{ab}(T,0)$ is linear at high temperatures in the optimal doping state, the usual way is to assume a linear decrease well above T_c and then to subtract it from the measured resistivity. However, this procedure cannot be justified except when reasonable values of the physical parameters are obtained. Furthermore, $\rho_c(T,0)$ in the normal state is still not well understood. Thus, the subtraction of the background resistivity from the measured resistivity in the mean-field region can yield arbitrary physical parameters when analyzing the data. To avoid this, instead of the zero-field fluctuation conductivity, we analyzed the fluctuation-induced magnetoconductivity $\Delta\sigma(T,H)$ first:

$$\Delta\sigma(T,H)=\sigma(T,H)-\sigma(T,0)=1/\rho(T,H)-1/\rho(T,0) \approx -\Delta\rho(T,H)/\rho(T,0)^2. \tag{1}$$

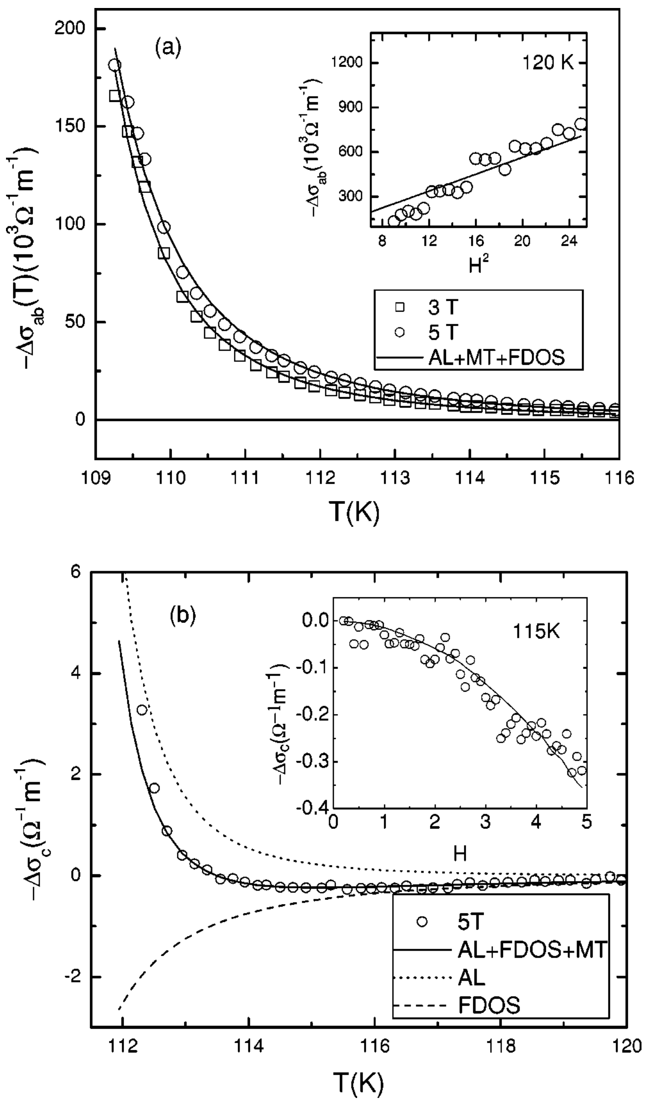

FIG. 2. (a) In-plane fluctuation-induced magnetoconductivity $\Delta\sigma_{ab}(T,H)$ at 3 and 5 T as functions of the temperature. The solid lines are the calculations from the theory of Dorin *et al.* The inset shows the field dependence of the in-plane fluctuation-induced magnetoconductivity. The solid line in the inset represents the theoretical curve calculated using the parameters obtained in an analysis of the main graph. (b) Out-of-plane fluctuation-induced magnetoconductivity $\Delta\sigma_c(T,H)$ at 5 T as a function of the temperature. The solid line is the calculation from the theory of Dorin *et al.*, the dotted line represents the contribution from the AL term and the dashed line the FDOS term. The inset shows the field dependence of the out-of-plane induced magnetoconductivity and the solid line in the inset represents the theoretical curve calculated using the parameters obtained in an analysis of the main graph.

In Fig. 2, $\Delta\sigma_{ab}(T,H)$ and $\Delta\sigma_c(T,H)$ are presented. The notable feature of these data is the sign change in $-\Delta\sigma_c(T,H)$ from negative at high temperatures to positive at low temperatures. This behavior has also been observed in other HTSC's (Refs. 27–31) and has been explained on the basis of FDOS contributions.

To explain the experimental data quantitatively, we used the theory of Dorin *et al.*, which includes the AL, MT, and

FDOS contributions.[11] In that theory, the total fluctuation conductivity is

$$\Delta\sigma(T,H)=\Delta\sigma_{\mathrm{AL}}(T,H)+\Delta\sigma_{\mathrm{FDOS}}(T,H)+\Delta\sigma_{\mathrm{MT}}^{\mathrm{reg}}(T,H)+\Delta\sigma_{\mathrm{MT}}^{\mathrm{an}}(T,H), \quad (2)$$

where $\Delta\sigma_{\mathrm{AL}}(T,H)$, $\Delta\sigma_{\mathrm{FDOS}}(T,H)$, $\Delta\sigma_{\mathrm{MT}}^{\mathrm{reg}}(T,H)$, and $\Delta\sigma_{\mathrm{MT}}^{\mathrm{an}}(T,H)$ result from the AL, the FDOS, the regular MT, and the anomalous MT contributions, respectively. It is to be noted that in this theory, only the orbital contributions were considered and spin interactions, i.e., the Zeeman effect, were neglected. However, since the Zeeman effect is important for $B\perp c$ and at reduced temperatures $(T-T_c^{mf})/T_c^{mf}>0.3$ for $B\|c$, the Zeeman terms are irrelevant in our case.[28] For our field strengths, the weak-field limit expressions are valid because the applied field is much smaller than the upper critical field at zero temperature. The details of the expressions for each contribution in the weak-field limit are given in Ref. 11. To fit the data, we varied the parameters $r=4\eta J^2k_B^2/v_F^2\hbar^2$, τ, τ_ϕ, $\beta=4\eta eB/\hbar$, and T_c^{mf}. Here, r is the anisotropy parameter, J is the effective interlayer energy in K, v_F is the Fermi velocity, τ is the quasiparticle scattering time, τ_ϕ is the pair-breaking lifetime, and T_c^{mf} is the mean-field temperature. The initial value of T_c^{mf} was obtained from the inflection point in the $d\rho(T)/dT$ curve and was allowed to vary within a limited range of less than 1 K. The solid lines in Fig. 2 represent calculations using the weak-field limit expressions for both directions. For $\Delta\sigma_c(T,H)$, the AL and the DOS contributions are also plotted separately in Fig. 2(b) but for clarity, the MT contribution was omitted.

The theory reproduces both $\Delta\sigma_{ab}(T,H)$ and $\Delta\sigma_c(T,H)$ fairly well. The AL term dominates at low temperatures, and the FDOS term dominates at high temperatures. The competition between AL and FDOS results in a sign change in $\Delta\sigma_c(T,H)$. The change of sign in $\Delta\sigma_c(T,H)$ was also observed in underdoped and optimally doped $Bi_2Sr_2CaCu_2O_8$ (Ref. 29) and optimally doped $YBa_2Cu_3O_{7-\delta}$ (Ref. 27) while it was not observed in overdoped $Bi_2Sr_2CaCu_2O_8$.[29] This doping dependence and the tendency toward negative MR in $\rho_c(T)$ is known to be correlated with the anisotropy of the material. As the doping content is decreased, the anisotropy increases. Therefore, the tendency of the sign change and the negative MR is enhanced when the number of hole carriers decreases. The physical parameters for this fitting will be discussed later.

The inset of Fig. 2 shows the field dependence of $\Delta\sigma_{ab}(T=120\ \mathrm{K},H)$ and $\Delta\sigma_c(T=115\ \mathrm{K},H)$. This graph clearly reveals that the sign of $-\Delta\sigma(H)$ (or MR) is positive in the ab plane and negative along the c axis. This anisotropy in MR is not explained within the Fermi liquid theory. Thus Anderson proposed a model that introduced two different carrier scattering rates far above T_c; one scattering rate dominated the longitudinal transport while the other governed the transverse one.[48] There was an experimental investigation of the MR of which behaviors were interpreted based on this scenarios.[6] However, ascribing the MR to normal-state properties is difficult in our case. Because our measurements were performed near T_c, the normal-state MR should be negligible compared with the fluctuation-induced magnetoresistivity. This was confirmed in $Bi_2Sr_2CaCu_2O_8$ for which detailed experimental investigations of the MR revealed that the normal-state magnetoresistivity appeared only above T_c+25 K and that below this temperature, fluctuations dominated the MR.[28] The solid lines in the inset of Fig. 2 are theoretical curves of $\Delta\sigma_{ab}(T=120\ \mathrm{K},H)$ and $\Delta\sigma_c(T=115\ \mathrm{K},H)$, which were plotted using the parameters obtained from $\Delta\sigma(T,H)$. The different behaviors of MR in the ab plane and along the c axis are well explained by using the effects of fluctuations on the conductivity.

Now let us explain the results for $\Delta\sigma(T,0)$. As mentioned above, for estimating ab-plane background resistivity the resistivity above 150 K was fitted by linear function $\rho_{ab}(0)+\mathrm{AT}$, as shown by solid line in inset of Fig 1(a). The behavior along the c direction, however, was totally different. The shape of $\rho_c(T)$ reveals a metallic resistivity at high temperatures and an insulating one at lower temperatures. These two regions are separated by a minimum value of ρ_c, ρ_c^{min}. In the normal-state above 150 K, $\rho_c(T)$ could be fitted by using the equation $\rho_c(T)=\rho_c(0)+BT+C/T$, as shown by solid line in inset of Fig 1(b), where the last term, which was proposed by Anderson and Zou,[14] arises due to the tunneling of electrons between the CuO_2 planes. In our analysis, the background region of $150\ \mathrm{K}<T<300$ K did not influence the results because the data were restricted to those below 1.3 T_c^{mf}, where the change in the background region hardly affects the data and the theory of Dorin *et al.* is valid.

$\Delta\sigma(T,0)$ in the ab plane and along the c direction are shown in Fig. 3. Here, the fluctuation conductivity was defined as $\Delta\sigma(T)=1/\rho(T)-1/\rho_n(T)$, where $\rho_n(T)$ is the normal-state background resistivity. We first compared the in-plane resistivity data with the AL contribution. In this analysis, variables were r, T_c^{mf}, and the interlayer distance s. However, the data could not be described without s being anomalously large. Even the possible maximum error of 30% in the magnitude of the resistvity due to the sample geometry cannot explain this large discrepancy between $s\approx 30$ Å obtained in the fitting and the actual value $s\approx 15$ Å. Moreover, when only the AL term was used, the data deviated from the theory systematically, especially at high temperatures, similar to an earlier report of the $Bi_2Sr_2CaCu_2O_8$ system.[49] The quality of the fitting became better when other indirect contributions, the FDOS and the MT terms, were included.

Some experimental reports have proposed that the in-plane paraconductivity, even in the region of $0.01<(T-T_c^{\mathrm{mf}})/T_c^{\mathrm{mf}}<\sim 1$, might be explained by using only the AL process with the proper energy cutoff.[50,51] However, since it will be very difficult to eliminate the effects of background subtraction in the above temperature range, the validity of those results should be carefully reexamined. Moreover, in this scenario, a unified explanation of $\Delta\rho_{ab}(T,0)$ and $\Delta\rho_c(T,0)$ is very difficult.

To obtain physical quantities, we included the AL, FDOS, and MT contributions. We used the initial values of the variables obtained from the previous analysis of the fluctuation-induced magnetoconductivity and restricted them to remain within a limited range. The results are shown in Fig. 3 with solid lines. The AL and the FDOS terms were plotted separately. The results reproduced the experimental data fairly

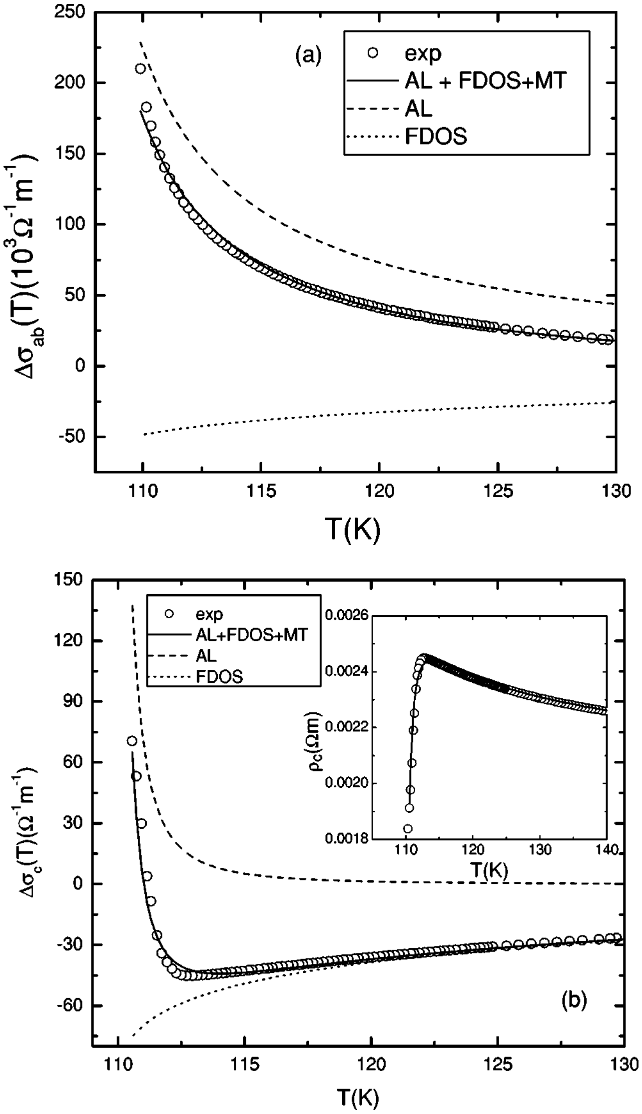

FIG. 3. (a) In-plane fluctuation conductivity $\Delta\sigma_{ab}(T,0)$ and (b) out-of-plane fluctuation conductivity $\Delta\sigma_c(T,0)$ as functions of the temperature. The solid line is the calculation from the theory of Dorin *et al.*, and the dotted and dashed lines represent the contributions from the FDOS and the AL terms, respectively. The inset of figure (b) shows the out-of-plane resistivity and the calculations. The subtraction of the normal-state resistivties is explained in the text.

well. Unlike the analysis that only considered the AL contribution, $\Delta\sigma_{ab}(T,0)$ was well described with $s\approx 14.7$ Å. For $\Delta\sigma_c(T,0)$, it was impossible to explain the data without the FDOS term. As in $\Delta\sigma_c(T,H)$, the FDOS term is dominant at high temperatures while the AL term is important at low temperatures. In the inset of Fig. 3(b), the calculated values of $\rho_c(T)$ are presented, along with the experimental data. The calculated $\rho_c(T)$ simulated the peak near T_c fairly well. This indicates that the peak in Tl2212 near T_c is due to the fluctuation conductivity, as originally proposed by Ioffe *et al.*[21] and Dorin *et al.*[11] and as later experimentally confirmed in $Bi_2Sr_2CaCu_2O_8$.[52]

The physical quantities obtained from both $\Delta\sigma(T,H)$ and $\Delta\sigma(T,0)$ are summarized in Table I. As far as we know, this is the first complete set of variables about ξ_{ab}, ξ_c, τ, τ_ϕ, and J in Tl2212. Thus, we had to compare these results with those of other HTSC's. The $\tau(100\text{ K})$ in Tl2212 is similar to $\tau(100\text{ K})=10-50$ fs in $Bi_2Sr_2CaCu_2O_8$, $(Tl,Hg)_2Ba_2Ca_2Cu_3O_{10+\delta}$, and $(Hg,Cu)Ba_2CuO_{4+\delta}$,[28–31,52] but is larger than $\tau(100\text{K})=3-5$ fs in $YBa_2Cu_3O_{7-\delta}$.[27,32–34] $\tau_\phi(100\text{ K})$ is larger than $\tau(100\text{ K})$, which was assumed by Dorin *et al.*[11] The values of J were reported for $Bi_2Sr_2CaCu_2O_8$ ($J=4.5-43$ K), $(Tl,Hg)_2Ba_2Ca_2Cu_3O_{10+\delta}$ ($J=4$ K), $(Hg,Cu)Ba_2CuO_{4+\delta}$($J=40$ K), and $YBa_2Cu_3O_{7-\delta}$($J=205-225$ K). From these values, the value of J for Tl2212 should be more similar to those for $Bi_2Sr_2CaCu_2O_8$ and $(Tl,Hg)_2Ba_2Ca_2Cu_3O_{10+\delta}$ than to those for $YBa_2Cu_3O_{7-\delta}$ even though the scattering of these values in one compound suggests that J depends on the doping state of the sample. This conclusion is fairly reasonable because the anisotropy of $Bi_2Sr_2CaCu_2O_8$ is known to be larger than that of $YBa_2Cu_3O_{7-\delta}$ but similar to that of Tl2212. The structure of Tl2212, which is similar to that of $Bi_2Sr_2CaCu_2O_8$, also supports this conclusion. The value of v_F in Tl2212 is $\approx 3\times 10^7$ cm/s, and this is also similar to the value reported for $Bi_2Sr_2CaCu_2O_8$,[28] but smaller than other reported values[29–31,52] for $Bi_2Sr_2CaCu_2O_8$. According to Dorin *et al.*,[11] the effective interlayer tunneling rate is of the order $k_B^2J^2\tau/\hbar^2$. In Tl2212, $k_B^2J^2\tau/\hbar^2 \ll \tau_\phi^{-1} < \tau^{-1}$, which suggests that the tunneling to neighboring layers is an incoherent event. From T_c^{mf}, τ, τ_ϕ, and J, we could calculate the coherence lengths ξ_{ab} and ξ_c. The values of ξ_{ab} and ξ_c were 12 ± 1 and 1.0 ± 0.2 Å, respectively. The value of ξ_{ab} is in good agreement with the value of 14.3 Å obtained from a reversible magnetization study.[39]

Finally, we will mention the out-of-plane normal-state resistivity. In the analysis of $\Delta\sigma_c(T,0)$, we assumed a temperature dependence of $\rho_c(0)+BT+C/T$, and the physical parameters so obtained were consistent with those in the analysis of $\Delta\sigma_c(T,H)$. This implies that the functional dependence of the out-of-plane normal-state resistivity was well described as suggested by Anderson *et al.*[14] A proposed activation-type formula $\rho_c(T)=A+BT+(C/T)\exp(\Delta/T)^3$ with $\Delta\approx 400$ K, could fit $\rho_c(T)$ down to the peak region where Δ was interpreted as the pseudogap. This implies that if this formula is correct, the fluctuation effects are negligible in $\rho_c(T)$ but understanding this behavior is very difficult.

TABLE I. Physical parameters obtained from the analysis of $\Delta\sigma(T,0)$ and $\Delta\sigma(T,H)$.

	T_c^{mf} (K)	ξ_{ab} (Å)	ξ_c (Å)	$\tau(100\text{ K})$ (*fs*)	$\tau_\phi(100\text{ K})$ (*fs*)	v_F (10^7 cm/s)	J (K)
$\Delta\sigma_{ab}$	107 ± 0.5	11 ± 1	1.0 ± 0.2	15 ± 3	20 ± 5		6.2
$\Delta\sigma_c$	110 ± 1	12 ± 1	0.7	20 ± 4	30 ± 5	3 ± 1	$\approx$

Moreover, the fitted value of Δ is too high for the optimally doped samples when compared with the transition temperature of underdoped $Bi_2Sr_2CaCu_2O_8$ single crystals with comparable values of Δ.[53]

IV. CONCLUSIONS

We investigated the in-plane and the out-of-plane zero-field fluctuation conductivity and fluctuation-induced magnetoconductivity of Tl2212 single crystals and analyzed those data based on a theory of fluctuation conductivity that included AL, MT, and FDOS contributions. This theory successfully explained not only the excess conductivity but also the positive in-plane magnetoresistance and negative out-of-plane magnetoresistance with reasonable values of the physical parameters. Furthermore, the peak in the *c*-axis resistivity was well described by the same effects as in other HTSC's.

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