Conductivity fluctuations in a single crystal of $Bi_2Sr_2CaCu_2O_x$

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We present an analysis of the measured excess conductivity that results from the fluctuations of the superconducting order parameter for a single crystal of the $Bi_2Sr_2CaCu_2O_x$ high-T_c superconductor. The measured excess conductivity in the temperature range 84–245 K is best fitted by the two-dimensional (2D) Aslamazov-Larkin theory. By using this theory, the 2D characteristic length was obtained to be 12.6 Å, which is within a physically acceptable range. We find that the interlayer coupling strength predicted by the Lawrence-Doniach theory leads to too small a value of the *c*-direction coherence length. This seems to be an intrinsic property of this superconductor due to its high anisotropy. Further, the indirect Maki-Thompson effect is found to be negligible. Thus we claim that the excess conductivity of the $Bi_2Sr_2CaCu_2O_x$ single crystal is solely caused by the two-dimensional thermal fluctuations of the order parameter with the absence of the 2D-3D crossover and that the effect of fluctuating Cooper pairs in association with pair breakers is negligible in considering the excess conductivity.

I. INTRODUCTION

High-T_c superconductors are known to have a relatively broad resistive transition. This is known to be largely caused by the thermal fluctuations of the superconducting order parameter. These thermal fluctuations allow a finite probability of forming superconducting electron pairs above T_c, and thus induce excess conductivity (or paraconductivity). The functional form of the excess conductivity depends on the dimensionality of fluctuations due to the nucleation and decay of superconducting droplets above T_c, or a dimensional crossover between two and three dimensions due to the interlayer coupling by the Josephson tunneling. Since anisotropy is significant in high-T_c superconductors, a careful examination of the dimensionality of transport is of great importance.

A number of studies on the excess conductivity for $Y_1Ba_2Cu_3O_x$ systems were done by using various fitting schemes. For polycrystalline bulk systems,[1–5] most analyses are consistent with the characteristics of three-dimensional (3D) thermal fluctuations. However, for the highly *c*-axis-oriented epitaxial thin films Oh *et al.*[6] reported that the 2D-3D crossover was observed. According to Pogrebnyakov *et al.*,[7] the dominance of 3D fluctuations, or 2D-3D crossover depended on the range of temperature. For single crystals,[8,9] different experimental results have been reported. Hagen *et al.*[8] reported that the dominance of 2D fluctuations. However, their results are inconsistent in that the zero-resistance transition temperature ($T_c^{R=0}$) was found to be higher than T_c^{MF}, the mean-field transition temperature. On the other hand, Friedmann *et al.*[9] reported that the Lawrence--Doniach theory gave the best fit to their data showing the 2D-3D crossover at $T_o=91.1$ K. Again T_c^{MF} below $T_c^{R=0}$ was obtained from their study, including an unreasonably small value of the coherence length.

For the $Bi_2Sr_2CaCu_2O_x$ or $Bi_2Sr_2Ca_2Cu_3O_x$ samples, most studies of excess conductivity have revealed the dominance of 2D fluctuations.[10–15] This observation is remarkably different from that of the $Y_1Ba_2Cu_3O_x$ superconductors, in which the 2D-3D crossover is often claimed to be present. Balestrino *et al.*[11] suggested the presence of 2D fluctuations. Using the Lawrence-Doniach theory, which can be applied to the 2D-3D crossover, Ravi *et al.*[12] reported a similar result with the 110-K polycrystal and Vidal *et al.*[10] with the 80-K phase polycrystal. Wnuk *et al.*[15] also observed the 2D fluctuations in both the Pb-doped 80-K phase and the Pb-doped 110-K phase single crystals. However, for the single crystal of $Bi_2Sr_2CaCu_2O_x$, Mandal *et al.*[14] reported a conflicting result by claiming that the 2D-3D crossover is present.

Conflicting interpretations of the excess conductivity may come from the difficulty of assessing the intrinsic properties of the samples. Different choices for the mean-field transition temperature T_c^{MF} and of the temperature range of fluctuations may yield such conflicting explanation when assessing the conduction mechanism. The best-fitted parameters for T_c^{MF} and the coherence length ξ, in order to reproduce observed excess conductivities, are often physically meaningless and thus are not reliable. For a valid claim, one must be careful in choosing such parameters in order to find a proper conduction mechanism.

We measured the conductivity of a high quality

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$Bi_2Sr_2CaCu_2O_x$ single crystal prepared by the self-flux method with a CuO-rich environment.[16] We applied the Aslamazov-Larkin (AL), the Lawrence-Doniach (LD) and the Maki-Thompson (MT) theories to analyze the rounding near the transition. The zero-resistance transition temperature $T_c^{R=0}$ of this superconductor is 79 K, and the normal resistivity $\rho(T=245\ \mathrm{K})$ is 3.97×10^{-4} Ω cm, which is smaller than others.[17,18] This proves that the quality of our single crystal is excellent. In the present analysis we obtained T_c^{MF}, the normal conductivity, the characteristic length, and the exponent associated with the dimensionality of transport by performing a remarkably consistent fit to our observed data. For further confirmation, we examined conduction due to fluctuations by using the values of previously investigated fitting parameters. Contrary to the report of Mandal *et al.*,[14] our study of the $Bi_2Sr_2CaCu_2O_x$ single crystal clearly reveals a definitive 2D conduction mechanism with the absence of the 2D-3D crossover.

II. A BRIEF REVIEW OF THEORIES FOR ANALYSIS

The total conductivity σ is given by the sum of the normal conductivity σ_n and the excess conductivity $\Delta\sigma$,

$$\sigma=\sigma_n+\Delta\sigma\ . \tag{1}$$

For computing $\Delta\sigma$, Aslamazov and Larkin[19] took into account the electric-field acceleration of the short-lived superconducting electron pairs which form above T_c.[9] The functional form of this excess conductivity varies with the dimensionality of superconductivity,

$$\Delta\sigma_{2\mathrm{D}}=(e^2/16\hbar d)t^{-1}\ , \tag{2}$$

$$\Delta\sigma_{3\mathrm{D}}=[e^2/32\hbar\xi(0)]t^{-1/2}\ , \tag{3}$$

where d is a two-dimensional characteristic length, $\xi(0)$ is a zero-temperature coherence length, and t is the reduced temperature, $t=(T-T_c^{\mathrm{MF}})/T_c^{\mathrm{MF}}$.

Lawrence and Doniach[32] considered a situation in which conduction occurs mainly in two-dimensional planes and where these planes are coupled by Josephson tunneling. The excess conductivity is given by

$$\Delta\sigma_{\mathrm{LD}}=\frac{e^2}{16\hbar d}t^{-1}\left[1+\left[\frac{2\xi_c(0)}{d}\right]t^{-1}\right]^{-1/2}\ . \tag{4}$$

There exists a 2D-3D crossover temperature T_o, $T_o=T_c^{\mathrm{MF}}\exp\{[2\xi_c(0)/d]^2\}$; for $T>T_o$, the Lawrence-Doniach theory reduces to the 2D Aslamazov-Larkin theory, and for $T<T_o$, it leads to the 3D theory.

Maki and Thompson[21,22] corrected the Aslamazov-Larkin theory by considering indirect effects for the decay of the superconducting pairs into quasiparticles, and vice-versa. The quasiparticle contribution to the conductivity during the breaking and reformation of the Cooper pairs is resolved by strong inelastic scatterers and by pair-breaking interaction. The Maki-Thompson correction, including the indirect effects described above, is given by

$$\Delta\sigma_{\mathrm{MT}}=\frac{e^2}{8\hbar d(t-\delta)}\ln\left[\frac{t}{\delta}\right]\ , \tag{5}$$

where $\delta=(T_{\mathrm{MT}}-T_c^{R=0})/T_c^{R=0}$ is the reduced temperature shift induced by pair-breaking interactions. This correction term is then added to the 2D or 3D term of Aslamazov-Larkin theory to compute the excess conductivity.

Mean-field approaches fail in a region near T_c^{MF} where thermal fluctuations become considerable. This temperature range can be obtained by the so-called Ginzburg criterion. Fluctuations of superconducting order parameter Ψ become larger than Ψ itself[23] when

$$|T-T_c^{\mathrm{MF}}|<1.07\times10^{-9}\frac{\kappa^4(T_c^{\mathrm{MF}})^3}{H_{c2}(0)}\ , \tag{6}$$

with $\kappa=\lambda/\xi$, $\lambda=$ penetration depth, and $\xi=$coherence length. For conventional superconductors, the Ginzburg criterion is $|T-T_c^{\mathrm{MF}}|<10^{-6}$ K. But the high values of T_c^{MF} and κ in high-T_c superconductors cause the Ginzburg-Landau theory to break down within 0.1 K or more of T_c^{MF}.

III. RESULTS AND DISCUSSIONS

The functional form of the total conductivity of the Aslamazov-Larkin theory is

$$\sigma(T)=[1/(AT+B)]+Ct^{-x}\ , \tag{7}$$

where $C=e^2/(16\hbar d)$ for 2D, or $C=e^2/[32\hbar\xi(0)]$ for 3D. The exponent x is 1 for 2D and $\frac{1}{2}$ for 3D.

Since $\Delta\sigma$ does not vanish even well above the transition temperature, one must fit σ to various theories not only with the parameters which appear in the expression of $\Delta\sigma$ but also with the parameters A and B for a relatively wide range of temperatures covering a normal-state region. The initial values of A and B for the normal-state conductivity were obtained by fitting the experimental value of σ to $1/(AT+B)$ for temperatures from 125 to 245 K. The lower bound of temperature for the whole fitting region of σ was chosen to be 84 K at which all the free fitting parameters were found to be stable. These parameters were observed to be not so sensitive to the choice of the upper bound of the fitting region.

We first fitted σ to Eq. (7). The results of fitting parameters from this fit are shown in Table I. The best exponent x after five-parameter fitting was found to be 1.06. This is far from the value of $\frac{1}{2}$ for the 3D Aslamazov-Larkin theory, but very close to 1 for the 2D theory. Encouraged by this result, we fitted our experimental data to the exact 2D Aslamazov-Larkin theory with $x=1$, in the same manner as discussed above. This result is shown in Fig. 1. Since x was already determined, the remaining four parameters A, B, C, and T_c^{MF} were to be carefully adjusted. The values obtained for d and T_c^{MF} are 12.6 Å and 81.5 K, respectively, as shown in Table I. The two-dimensional characteristic length d is larger than the thickness 4.5 Å of the conducting double CuO_2 planes, but smaller than the c-axis unit-cell size 30.7 Å for $Bi_2Sr_2CaCu_2O_x$. Superconductivity occurs mainly in the region within ~4 Å from the double CuO_2 layers, but does not extend its range of transport to the neighboring conducting layers. Encouragingly, T_c^{MF} obtained from

TABLE I. The results of fittings. $\chi^2=(1/N)\sum_i^N(\sigma-\sigma_{exp})_i^2$, N is the total number of data points used for the fit.

	A (10^{-7} Ω cm/K)	B (10^{-5} Ω cm)	C (Ω cm)	T_c^{MF} (K)	χ^2
2D AL theory	9.39	1.80	81.51	81.51	1.373
3D AL theory	8.95	2.50	82.90	82.90	2.153
[a]exponent-AL	9.48	1.80	81.34	81.34	1.367
[b]MT theory	9.49	1.80	81.56	81.56	1.376
[c]LD theory	9.42	1.80	81.68	81.68	1.376

[a]AL exp: fitting to the Aslamazov-Larkin theory using the exponent of t in the theory as a free parameter, the result of fit, $x=1.06$.
[b]MT reduced temperature shift $\delta=7.85$.
[c]LD coupling strength $l=[2\xi_c(0)/d]^2=4.06\times10^{-3}$.

our fitting procedure is higher than $T_c^{R=0}$. In addition, we found that T_c^{MF} is neither a half-resistance transition temperature nor the temperature of the inflection point of temperature to resistivity.

We also fitted our resistivity data to the 3D Aslamazov-Larkin theory with $x=\frac{1}{2}$. The result was poorer than the fit to the 2D Aslamazov-Larkin theory. We obtained the zero-temperature coherence length $\xi(0)$ of 1.36 Å, which is much smaller than half the distance between the conducting CuO_2 layers. This unreasonably small coherence length ruled out the validity of the 3D thermal fluctuations of the superconducting order parameter for explaining the excess conductivity. We now examine the Maki-Thompson effect by considering the correction term of Eq. (4), which is to be added to Eq. (7). Our result was almost the same as the 2D Aslamazov-Larkin theory fit discussed above. The Maki-Thompson correction was found to be in the order of 10^{-6}, compared to the 2D Aslamazov-Larkin term. Thus the

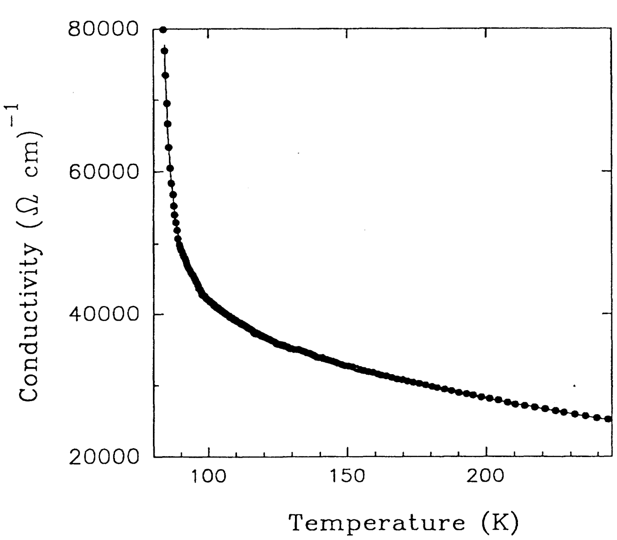

FIG. 1. The excess conductivity fit of $Bi_2Sr_2CaCu_2O_x$ to the mean-field theories in the temperature range from 84 to 245 K. All the other fittings have almost same as 2D fit. However, their fitting parameters are nonphysical. (Details discussed in the text; filled circle=experimental data, line=2D fit.)

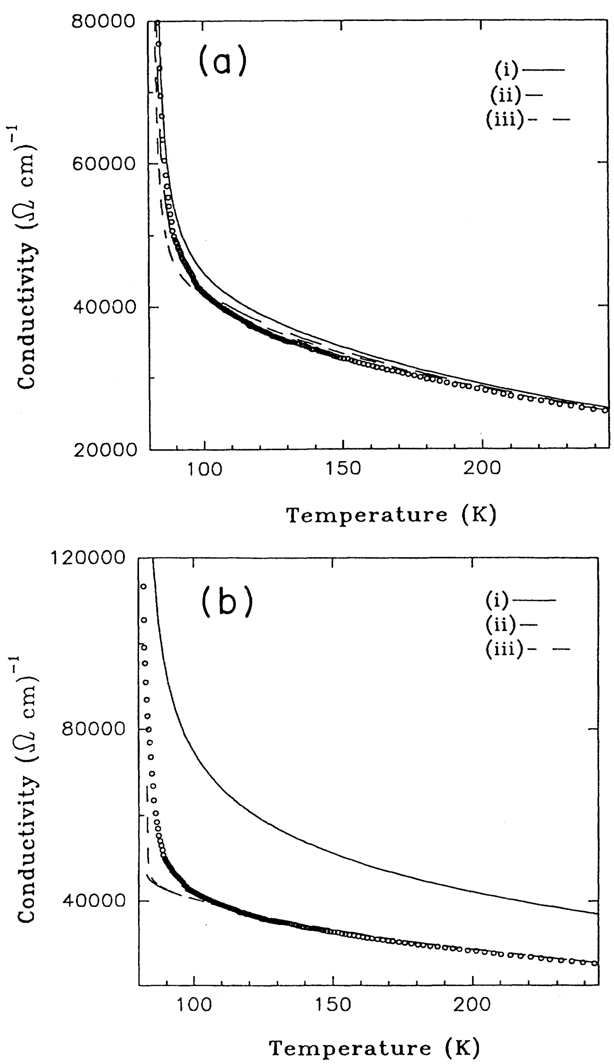

FIG. 2. The calculations of total conductivity using the published values of ξ and d. The 2D conduction is obvious for the excess conductivity of $Bi_2Sr_2CaCu_2O_x$. (hollow circle=experimental data, lines=calculated by using the experimental values). (a) the 2D Aslamazov-Larkin theory: (i) $d=5$ Å, (ii) $d=12$ Å, (iii) $d=30.7$ Å. (b) the 3D Aslamazov-Larkin theory: (i) $\xi_c=0.45$ Å, (ii) $\xi_{av}=14$ Å, (iii) $\xi_{av}=14$ Å, $T_c^{MF}=82.9$ K.

Maki-Thompson effect is negligible compared to the dominant 2D thermal fluctuations leading to the nucleation and decay of superconducting droplets which exist above T_c in $Bi_2Sr_2CaCu_2O_x$ (BSCCO).

Finally, we examined the effect of the interlayer coupling due to Josephson tunneling proposed by Lawrence and Doniach. The results are shown in Table I. The 2D-3D crossover temperature $T_o = T_c^{MF}\exp\{[2\xi_c(0)/d]^2\}$ is 82.0 K. This crossover temperature is within the Ginzburg criterion where the mean-field theories break down. A zero-temperature coherence length $\xi(0) = 0.4$ Å is too small to induce coupling in the c direction, but this value is very similar to experimental result. So, we claim that the absence of the 2D-3D crossover is intrinsic due to high anisotropy of BSCCO systems. For this reason, we conclude that the Lawrence-Doniach theory cannot be applicable to $Bi_2Sr_2CaCu_2O_x$.

Our findings above become more conclusive if we use real experimental values for d and ξ instead of using them as fitting parameters for the excess conductivity. We reanalyzed the total conductivity of Eq. (1). We used the mean-field transition temperature $T_c^{MF} = 81.6$ K obtained from the best fitting. For this analysis, we calculated the normal-state conductivity $\sigma_n = 1/(AT+B)$ in Eq. (1). The coefficients A and B were obtained by fitting the normal region from 125 to 245 K. A was 1.00×10^{-6} Ohm cm/K and B, 1.55×10^{-5} Ohm cm. These initial values of A and B were used to test each theories for $\Delta\sigma$.

First of all we compared our experimental data to the 2D Aslamazov-Larkin theory. We estimated the two-dimensional characteristic length d in Eq. (2), based on the structural characteristics of $Bi_2Sr_2CaCu_2O_x$. It is an important physical quantity in the 2D theory. We believe that the value of d should be at least greater than the thickness of the double CuO_2 layers ~ 4 Å for this superconducting material. However this should not be greater than the c-axis unit-cell length of 30.7 Å (Refs. 24 and 25) because in this case the conduction of Cooper pairs extended to the next layers, and gives 3D transport properties not 2D. This is obvious from Fig. 2(a), where we find that the excess conductivity is originated from the 2D thermal fluctuations with the range of d mentioned above. This is a reasonable result if we consider negligible coupling to the c direction of the superconducting electrons from the main conduction layers. We calculated also the excess conductivity by assuming the 3D fluctuations as a main cause of this conductivity. We used the coherence length ξ in the Eq. (3) with the published values,[26] of $\xi_c(0.45$ Å$)$, $\xi_{ab}(27$ Å$)$ and their average. However, as seen in Fig. 2(b), the data from the 3D theory deviate considerably from the experimental value for both of the averaged and anisotropic values of ξ. This 3D theory does not fit even for $T_c^{MF} = 82.9$ K, which is the result of the 3D best fit.

IV. CONCLUSIONS

We measured the conductivity of the $Bi_2Sr_2CaCu_2O_x$ single crystal and discussed the role of the thermal fluctuations of the superconducting order parameter on the excess conductivity near the resistive transition. We first analyzed the excess conductivity by fitting the mean-field theories and by applying the Ginzburg criterion based on rigorously self-consistent choice of parameters. Contrary to the previous work,[14] the excess conductivity of this single crystal was found to be best fitted by the 2D Aslamazov-Larkin theory with the absence of the 2D-3D crossover. Our values for various physical parameters were not only self-consistent but also within well acceptable ranges. We noted that the interlayer coupling by Josephson tunneling leads to a very small value of coherence length at zero temperature, and thus the Lawrence-Doniach theory is not applicable for this highly anisotropic superconductor. We also found that the Maki-Thompson correction to incorporate the additional effects of pair fluctuations is negligibly small. We made an additional analysis by applying the measured physical quantities for the parameters from a previous fitting. From this result, we are confident that conclusions made above are valid for the $Bi_2Sr_2CaCu_2O_x$ single crystal.

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