Resistive transition in $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ phase

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The electrical resistance of c-oriented $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ platelets near the superconducting transition has been studied. The analysis of data was performed self-consistently in terms of the Aslamazov–Larkin theory of the fluctuation conductivity well above the transition and in the context of the Coulomb gas analogy for vortex fluctuations at temperatures below the mean-field transition temperature. We found for the first time the values of the anisotropy parameter and the effective interlayer hopping energy in $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ phase. © *1994 American Institute of Physics.*

The temperature dependence of the electrical resistivity $\rho(T)$ near the superconducting transition is one of the main characteristics of a superconductor. The distinctive features of high-T_c superconductors, such as the large structural anisotropy and short coherence lengths, result in some inherent peculiarities in their resistivity temperature dependence. The first one concerns the pronounced effect of the fluctuations of order parameter above the mean-field (Ginzburg–Landau) critical temperature $T_{\rm GL}$. Such superconducting fluctuations determine both the in-plane ρ_{ab} and the out-of-plane ρ_c components of the resistivity tensor in the overall temperature range from $T_{\rm GL}$ up to roughly[1,2] $2T_{\rm GL}$. Another important peculiarity is the manifestation of fluctuations of the phase of the order parameter below $T_{\rm GL}$, which lead to the strong reduction of the critical temperature by the external magnetic field due to melting of the vortex lattice.[3] In a zero magnetic field, these fluctuations manifest themselves as an additional dissipation caused by the dissociation of vortex–antivortex pairs at the temperature of the Kosterlitz–Thouless (KT) transitions $T_{\rm KT}$,[4] which lies below $T_{\rm GL}$. This results in an intrinsic broadening of the resistive transition with the characteristic parameter $\tau_c=(T_{\rm GL}-T_{\rm KT})/T_{\rm GL}\approx0.01$–$0.05$ for different high-T_c compounds.[5,6]

The purpose of the present paper is to study self-consistently the in-plane $\rho_{ab}(T)$ dependence for the $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (2223 BSCCO) phase within the fluctuation theory applied below and above the mean-field critical temperature. We analyze the overall $\rho_{ab}(T)$ in terms of the theory of paramagnetic conductivity above $T_{\rm GL}$ and the Coulomb gas model for vortex fluctuations based on the KT theory below $T_{\rm GL}$. Notice that the growth of single-crystals or well-oriented epitaxial films of the 2223 BSCCO phase presents severe problems, which makes it impossible to directly measure such an important characteristic of a layered material as the anisotropy of the resistivities, $\gamma=(\rho_c/\rho_{ab})^{1/2}$. This anisotropy parameter, which is directly connected with the effective quasiparticle interlayer hopping energy J, defines the pinning and vortex interaction energies in the layered superconductors.[7] and hence is crucial for understanding a number of properties of the superconducting state in high-T_c cuprates. We present here the first estimate of the γ and J values for the 2223 BSCCO phase.

The resistance measurements were carried out on single-phase 2223 BSCCO platelets grown by a novel method described in detail in Ref. 8. This method, which is based on a thermal gradient enhanced KCl flux, allows us to grow 2223 BSCCO platelets with a thickness of about 0.5 μm and a surface area of several mm^2. Using this technique, we grew platelets of the 2223 BSCCO phase in a time interval of about 10 mm (extremely short in comparison with that required for the formation of this phase by solid state reaction). Platelets were fully characterized by x-ray diffraction, microprobe analysis, and transport electrical measurements. They were found to be strictly c-oriented, to have a low residual resistance, and to have a sharp superconducting transition. To carry out resistance measurements, we used an original apparatus based on a pressurizable LAr bath, in order to obtain the sensitivity of the temperature control required for measurements very close to the critical region.[9] The sensitivity achieved in this way was better than 5 mK. The temperature was measured with a Lake Shore PT111 platinum sensor in a dc four-probe configuration by a six-digit Keithley multimeter. Resistance measurements were performed by the standard dc four-probe technique, using a μ-metal shield to avoid the influence of the external magnetic field on the measurements.

The temperature dependence of the in-plane resistance of our sample is shown in Fig. 1. The temperature of zero resistance, within the experimental error, is 100.5 K.

We start our analysis with the range of temperature above $T_{\rm GL}$, where the excess conductivity of several high-T_c cuprates was found to be well-described within the Aslamazov–Larkin (AL) theory of fluctuation paramagnetic conductivity.[10] The theoretical functional form for excess conductivity is

$$\sigma_{fl}=C_d\epsilon^{-n}, \qquad (1)$$

where $\epsilon=\ln(T/T_{\rm GL})\approx(T-T_{\rm GL})/T_{\rm GL}$ when $T-T_{\rm GL}\ll T_{\rm GL}$. In the 2D case we have $C_2=e^2/16s\hbar(n=1)$ and in the 3D case we have $C_3=e^2/16r^{1/2}s\hbar(n=1/2)$ (e is the electron charge, and s is the effective interplane distance). The quantity r is a parameter characterizing the dimensional crossover, from the 2D to the 3D regime in the thermodynamic fluctuation behavior:[11] $r(T_{\rm GL})=4\xi_c^2(0)/s^2$ where $\xi_c(0)$ is the zero-temperature Ginzburg–Landau coherence length in the direction of the c axis. The measured excess conductivity is $\sigma'=R^{-1}(T)-R_N^{-1}(T)$, where $R_N(T)$ is the normal-state resistance, extrapolated from high temperatures, vs ϵ is shown on a ln–ln scale in Fig. 2. The features of this plot are: (i) the 2D behavior of the fluctuation conductivity in the range of reduced temperatures $0.01<\epsilon<0.2$; (ii) the deviation from the form given by Eq. (1) at $\epsilon>0.2$, which is a manifestation of dynamical corrections to the 2D paramagnetic conductivity found in Ref. 12; (iii) the clear crossover to the 3D regime takes place as the temperature approaches $T_{\rm GL}$. The fit of experimental data to Eq. (1) in the 2D ($n=1$) and 3D ($n=1/2$) regimes gives: $T_{\rm GL}=106.2\pm0.1$ K, $C_2=3.28\pm0.01$ mΩ^{-1}, and $C_3=30.72\pm0.04$

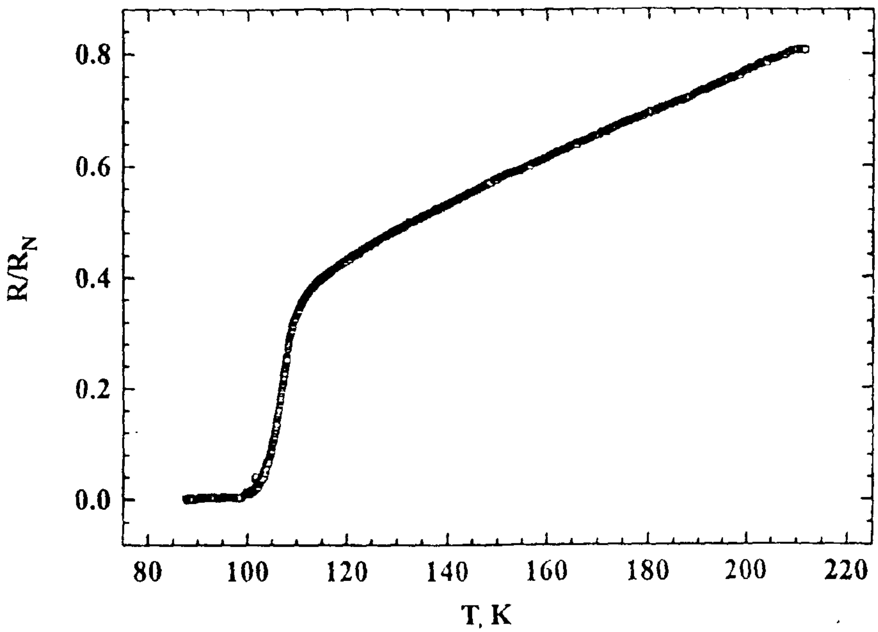

FIG. 1. Resistance-vs-temperature curve with a normalizing factor $R_N=31.6\ \Omega$.

$m\Omega^{-1}$. It is worth emphasizing that the irregular geometry of the platelet does not allow us to evaluate the absolute value of resistivity. Therefore, we cannot determine the interplane distance from the coefficients C_2 and C_3, using Eq. (1). Nevertheless, we can estimate the r parameter from the ratio: $r(T_{GL})=(C_2/C_3)^2=0.011$. The parameter r is directly related to the interlayer quasiparticle hopping energy J:[14]

$$r=-2\,\frac{J^2}{T^2}\,F(T\tau),\quad F(x)=x^2\left[\psi\left(\frac{1}{2}+\frac{1}{4\pi x}\right)-\psi\left(\frac{1}{2}\right)-\frac{1}{4\pi x}\,\psi'\left(\frac{1}{2}\right)\right], \tag{2}$$

where τ is the quasiparticle scattering time, and $\psi(x)$ and $\psi'(x)$ are the digamma function and its derivative, respectively. Assuming for temperatures close to T_{GL} $T\tau\approx 0.5-1$, in accordance with the values for other high-T_c cuprates,[13,6,14] and taking into account that the function $F(T\tau)$ changes slowly in this region [i.e., $F(0.5)=0.0046$, while $F(1)=0.0042$], we find for our case from Eq. (2) $J\approx 25-30$ K.

Our next step is to fit the resistance data below T_{GL}, using the Coulomb gas analogy of vortex fluctuations introduced by Minnhagen.[15] The interpretation of the resistivity data below T_{GL} in the two-dimensional superconductors is based on the following factors: the analogy between the physics of the Coulomb gas of particles and the vortices in the 2D superconductor, the KT charge-unbinding renormalization theory, and the Bardeen–Stephen model of flux-flow resistivity.[15] This approach was found to describe satisfactorily the resistivity of the "old" 2D superconductors, as well as high-T_c cuprates below the mean-field critical temperature.[16,6] In the context of this model, the resistance at the edge of the transition satisfies the scaling relation:[17,15]

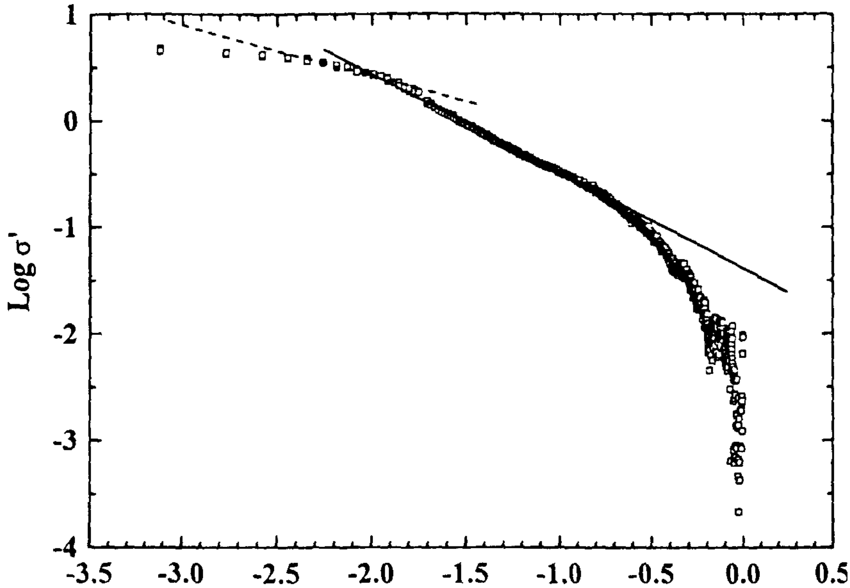

FIG. 2. Excess conductivity σ' vs $(T-T_{\mathrm{GL}})/T_{\mathrm{GL}}$ in a ln–ln scale. The solid line represents the 2D Aslamazov–Larkin result with $T_{\mathrm{GL}}=106.2$ K, $C_2=3.28\ \mathrm{m}\Omega^{-1}$; the dashed line represents the 3D result with the same T_{GL} and $C_3=30.72\ \mathrm{m}\Omega^{-1}$.

$$\frac{R}{R_N}=A\ \exp\left[-2b\left(\frac{T_{\mathrm{GL}}-T}{T-T_{\mathrm{KT}}}\right)^{1/2}\right]. \tag{3}$$

Here A and b are the nonuniversal constants of order unity, which depend on the sample characteristics. Equation (2) describes the resistivity of the 2D superconductor in the temperature range between T_{KT} and T_{GL} and therefore can be applied to high-T_c cuprates only when the effects of the interlayer coupling are negligible. The problem of vortex fluctuations in quasi-2D superconductors (with finite Josephson coupling between layers) was recently widely discussed.[18] It was found that vortices can be considered two-dimensional only if the temperature exceeds the characteristic temperature:

$$T^*=T_{\mathrm{KT}}+\frac{T_{\mathrm{GL}}-T_{\mathrm{KT}}}{1+\frac{1}{b^2}\ln^2(\gamma s/\xi_{ab})} \tag{4}$$

(ξ_{ab} is the Ginzburg–Landau in-plane coherence length). Consequently, for temperatures $T^*<T<T_{\mathrm{GL}}$ Eq. (2) is still justified, while at lower temperatures a more comprehensive theory is required.

In Fig. 3 we have plotted the behavior of $\ln(R/R_N)$ as a function of temperature. The inset shows the same data in the $\ln(R/N_N)$–vs–reduced-temperature $[(T_{\mathrm{GL}}-T)/(T-T_{\mathrm{KT}})]^{1/2}$ plot. A good agreement with Eq. (2) is evident for temperatures from 106 K down to approximately 102 K. Fitting of data to Eq. (2) in the temperature

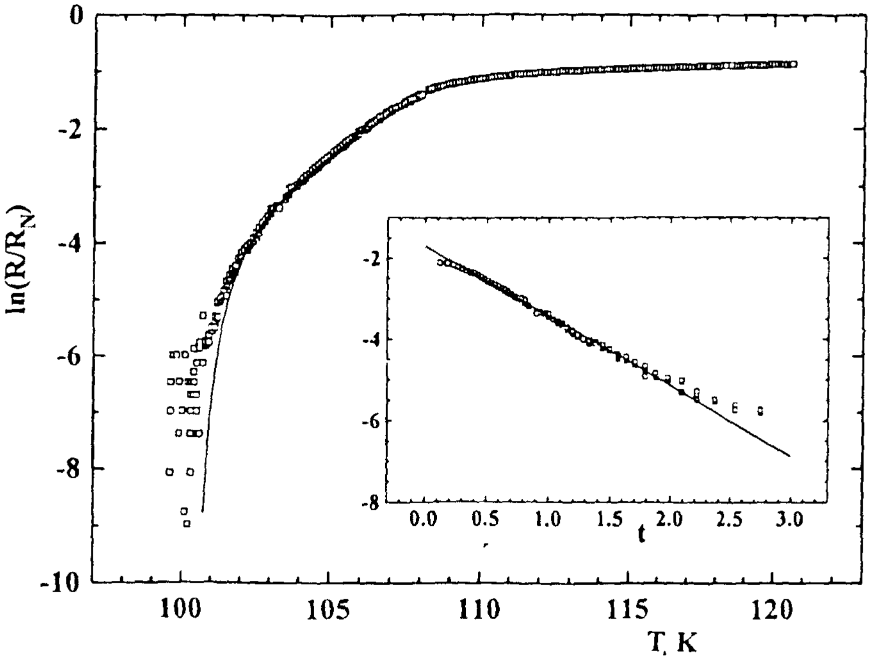

FIG. 3. Temperature dependence of the resistivity below T_{GL} in the $\ln(R/R_N)$-vs-temperature plot. The solid line represents the best fit to Eq. (3), with $T_{KT}=100.43$ K, $A=1.84$, $b=0.66$. The inset shows the $\ln(R/R_N)$-vs-reduced-temperature $t[(T_{GL}-T)/(T-T_{KT})]^{1/2}$ plot.

range 102–106 K gives: $T_{KT}=100.43$ K, $A=1.84\pm0.09$, and $b=0.66\pm0.09$. However, below 102 K the deviation from 2D behavior was found to be in analogy with the same analysis on 2212 BSSCO epitaxial films.[6] We attribute this deviation to the crossover from 2D to 3D vortex configuration.[19] Rough estimate of the γ parameter from Eq. (3) at $T^*\approx102$ K implies $\gamma\approx50$ [we adopt $s\approx\xi_{ab}(0)$].

Let us analyze the results which we obtained. The main issue is the consistency of our data with the AL theory of paramagnetic conductivity above T_{GL} and the Coulomb gas analogy for 2D vortex fluctuations modified to take into account the weak coupling between superconducting layers below T_{GL}. The parameters which we extracted from the fits of the data to the above theories are: $T_{GL}=106.2$ K, $T_{KT}=100.4$ K, $J=25$–30 K, and $\gamma\approx50$. The last estimate corresponds roughly to the γ factor found for 2212 BSCCO samples after thermal treatments in an oxidizing atmosphere, but is significantly lower than that for as-grown samples.[19] For the reduced intrinsic width of the transition we find: $\tau_c=0.054$, which is close to the values found earlier for several high-T_c compounds.[5,6] The important parameters which, to the best of our knowledge, we found for the first time, are the anisotropy factor γ and the effective interlayer hopping energy J. Comparing these values with those for the 2212 BSSCO phase, we must take into account that the effective anisotropy in Bi-based cuprates is extremely sensitive to the oxygen content. Such a comparison therefore makes sense only for samples which are in similar oxygenation states. Nevertheless, the data have shown that 2223 BSCCO phase is slightly less anisotropic than the 2212 BSSCO phase, because the clear 2D–3D crossover in the fluctuation conductivity has not been observed in the latter. The analysis of the data below T_{GL} confirms the scenario with the KT transition in the system of 3D vortex lines with their further dissociation into 2D pancakes at a temperature T^*. In summary we found, that peculiarities of the resistive transition in the 2223 BSCCO phase are consistent with the predictions of the fluctuation theory above and below the critical mean-field temperature.

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