Evidence of the temperature-dependent interlayer coupling from the anisotropic transport properties in Co-substituted single-crystal $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$

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We report on the effect of Co impurity substitution on the anisotropic transport properties of $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ single crystals. With Co doping, there is an increase in anisotropy γ estimated from the scaling of the angular dependence of the in-plane resistivity with reduced field as well as in the out-of-plane resistivity. These results can be quantitatively explained by the two-dimensional Lawrence-Doniach model, if we assume that the anisotropy in the superconducting state is determined by the interlayer coupling just above T_c. The analysis highlights the specific feature in high-T_c cuprates that the effective interlayer coupling depends on temperature. [S0163-1829(96)50234-1]

The highly anomalous transport[1] and optical[2] properties on the interlayer charge dynamics are key issues in high-T_c superconductivity.[3,4] However, whether or not the interlayer charge transport is inherently incoherent is still an open question. Furthermore, although many models have been proposed to explain ''semiconductive'' out-of-plane resistivity ρ_c, which is usually observed in the underdoped cuprates, there is no consensus as yet.[5]

We have previously shown that the impurity effect on the anisotropic transport properties is a sensitive probe for investigating the interlayer charge dynamics.[6,7] This approach is based on the idea that the impurity averages one-electron state according to its dimensionality. If the system is anisotropic three-dimensional (3D) (coherent in the interlayer charge transport), a reduction of the anisotropy can be expected through the averaging of the gap functions Δ since coherence length $\xi \propto \hbar v_F/\Delta$ from the clean limit BCS. Indeed, we have observed such impurity-induced reduction of the anisotropy ratio ξ_{ab}/ξ_c, where ξ_{ab} is the in-plane and ξ_c the out-of-plane coherence length, as well as an increase in ρ_c due to the impurity scattering in fully oxidized $Ba_2Y(Cu_{1-x}Zn_x)_3O_{7-\delta}$.[6] On the other hand, if the system is strictly 2D with almost no dispersion along the c axis (incoherent in the interlayer charge transport), the impurity causes averaging of only in-plane states and the system obeys the Lawrence-Doniach (LD) description.[8] As a result, in general, no change in the anisotropy or in the magnitude of ρ_c can be expected. These arguments are valid even when the superconductivity is non-*s* wave because they are derived only from the nature of the one-electron state, while ξ's themselves will increase due to the impurity pair breaking effect in the case of d-wave superconductivity.

In this paper, we investigate the impurity effect on the superconducting coherence length ξ and the normal-state transport properties ρ_a,ρ_c of $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ single crystals, focusing on the interlayer charge dynamics. The obtained anisotropic parameter value, $\gamma=\xi_{ab}/\xi_c=(m_c/m_{ab})^{1/2}$, and ρ_c increased with Co doping. These results were analyzed using the LD model. Based on this analysis, we discuss the mechanism causing ''semiconductive'' ρ_c. Here, to estimate anisotropy in the superconducting state, we first measured the in-plane resistive transition under various magnetic fields ($\mathbf{B}\|c$). Data were analyzed using the superconducting-fluctuation-renormalized Ginzburg-Landau (GL) theory (Ikeda *et al.*),[9] which has succeeded in explaining the characteristic broadening phenomena of the resistive transition. For more accurate estimation of γ, we then measured the in-plane resistivity ρ_a as a function of the magnetic field direction in the reversible regime. Scaling rules developed for strong type II superconductors (Blatter *et al.*),[10] were used for the analysis.

Single crystals were grown using the traveling solvent floating zone (TSFZ) method. TSFZ has a fundamental advantage that homogeneous impurity doping is possible. The single crystals were annealed in air at 600 °C for 24 h ~36 h, then rapidly cooled in air or slowly cooled under equilibrium oxygen pressures, which were controlled by oxygen and argon flow ratio, at each temperature. The latter process ensured both uniform oxygen content and minimum disorder in the crystals, which were used for the measurement of field direction dependence for the ρ_a as well as for the ρ_c measurement. We measured ρ_a with the standard four-probe method, while ρ_c was measured with a four-probe-like method with the voltage contacts attached to the center of the *ab* plane and the current contacts covering almost all of the remaining space.[11]

Figure 1 shows the temperature dependence of in-plane resistivities ρ_a for pure and Co 4% doped single-crystal $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$. The room-temperature value of ρ_a for pure sample is typically $\approx$250 $\mu\Omega$ cm. The temperature dependence is nearly linear, but contains a small quadratic component, suggesting the samples are in the overdoped region. Impurity (Co) doping to 4% primarily caused large ($\approx$160 $\mu\Omega$ cm) residual resistivity, which was estimated from the intercept of ρ_{a0}, the bare in-plane resistivity, where the effect of the superconductive fluctuation is eliminated, as shown below. It also caused a slight increase in the slope of $d\rho_a/dT$ from $\approx$0.83 $\mu\Omega$ cm/K for the pure sample to $\approx$1.2 $\mu\Omega$ cm/K for the doped one, implying the carrier concentration decreased slightly due to the trivalent Co substitution for Cu. However, the samples are overdoped even when Co is doped because tentative reductions in the oxygen content of these samples raised their T_c.

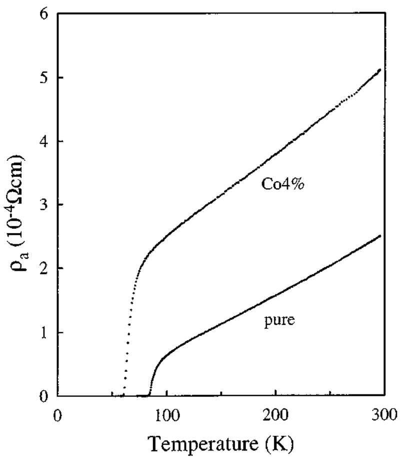

FIG. 1. In-plane resistivities ρ_a of $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ ($x=0,0.04$) single crystals versus temperature. The temperatures at which ρ_a becomes zero are 84 and 60 K for the pure ($x=0$) and Co 4% doped ($x=0.04$) samples, respectively.

Figures 2(a) and 2(b) show, respectively, the in-plane resistive transition under the various magnetic fields $\mathbf{B}(||c)$ for the pure and Co 4% doped single-crystal $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$. Theoretical fits plotted according to the fluctuation-renormalized GL theory[9] are also shown. In both sets of experimental data, there are large decreases in the ρ_a, probably due to the superconductive fluctuation, from far (20–30 K) above T_c and typical tailing behavior at low temperatures in the magnetic fields. These are caused by the fluctuation enhanced by the short coherence length, high T_c, electronic two-dimensionality, and the one-dimensionalization of the fluctuation under a high magnetic field. In the analysis, the ρ_{a0} was assumed to be a linear extrapolation of the resistivity at higher temperatures. Here, when there was no magnetic field, the well-known Aslamasov-Larkin (AL) type description for the fluctuation was assumed.[9] The analysis was done concentrating on the high-field data, because the model was justified in the high-field limit. The fitting reproduces well the characteristic features of the data, although it was not complete. The fact that the resistivity at low temperatures is smaller than that predicted by the theory suggests that a vortex motion begins to play some role in the dissipation. Although the theoretical formula used (AL fluctuation) is derived assuming conventional (s-wave) superconductivity, it is expected to be valid with possible changes in the numerical factors in the case of d-wave superconductivity, since it is based on the one-component GL theory. Actually, the reasonable fit results here for $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ and for $Ba_2Y(Cu_{1-x}Zn_x)_3O_{7-\delta}$ (Ref. 6) imply that the description based on one-component GL theory may not need much modification even in the case of d-wave superconductivity.

The obtained parameters, i.e., the mean field critical temperature T_{c0}, specific-heat jump ΔC, the phenomenological C factor, which adjusts the magnitude of the fluctuation effect, ξ_{ab}, and ξ_c are listed in Table I. The T_{c0} is slightly higher than the observed temperatures at zero resistivity with no magnetic field, suggesting the occurrence for Kosterlitz-Thouless (KT) like transition reflecting the two-dimensionality of the $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ system.[12] The ΔC values agree with the reported values[13] obtained by direct measurement. The C factors are smaller than 1, implying that the effect of the superconducting fluctuation is enhanced for some unknown reasons. A reasonable ξ_{ab} value for the pure sample is obtained. With Co doping, the ξ_{ab} value increased, probably due to the reduction of the gap Δ, since $\xi \propto \hbar v_F/\Delta$. The very small (0.1 Å) ξ_c in each system well reproduced the data, but the theoretical curve became insensitive for further reduction of ξ_c. Thus, the extreme anisotropy in the superconducting state for the pure $Bi_2Sr_2CaCu_2O_{8+\delta}$ system was found to be maintained upon Co doping. However, precise estimation of the change in the anisotropy is impossible from only the present analysis.

Next, ρ_a was measured as a function of the angle θ ($-15° < \theta < 5°$) between the a axis and the magnetic field $\mathbf{B}$ ($\mathbf{B}$ lies in the ac plane) in the reversible region [Figs. 3(a) and 3(b)]. Blatter *et al.* have shown[9] that the angle-dependent values of ρ_a under various constant fields $\mathbf{B}$ at a fixed temperature are scaled on one curve against the reduced field $B_{\rm red}=B(\sin^2\theta+\gamma^{-2}\cos^2\theta)^{1/2}$. Because this scaling rule is based on GL or London equations assuming only a strong type II superconductor, it is widely accepted to be valid for high-T_c cuprates[14] and is used to estimate anisotropic parameter γ. This way of obtaining γ has an advantage of higher accuracy, even in an extremely anisotropic case such as the $Bi_2Sr_2CaCu_2O_{8+\delta}$ system, than the analysis of temperature dependence for the resistive superconducting-transition described above. The experimen-

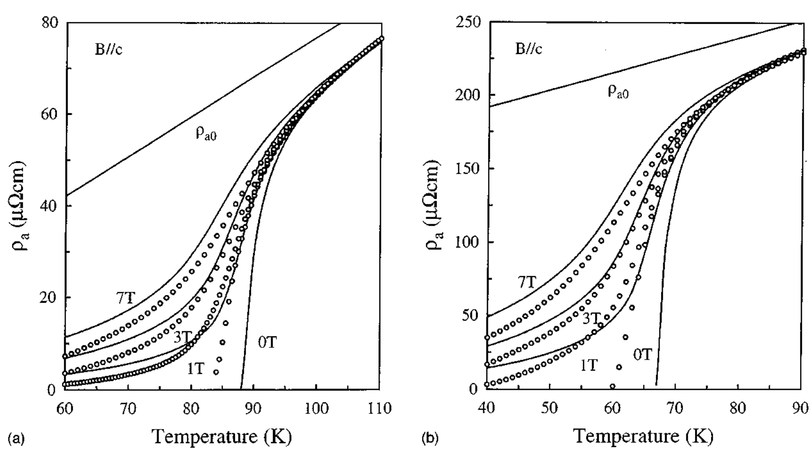

FIG. 2. In-plane resistive transitions of the same $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ single crystals in Fig. 1 when (a) $x=0$ and (b) $x=0.04$ under various magnetic fields perpendicular to the CuO_2 planes. The solid curves are the theoretical fits with the parameters listed in Table 1. The ρ_{a0} represents the in-plane resistivity when superconductive fluctuation effects were absent.

TABLE I. Parameters obtained by the theoretical fit for the resistive transition of single-crystal $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ ($x=0,0.04$) shown in Fig. 1.

Sample	Pure ($x=0$)	Co 4% doped ($x=0.04$)
T_{c0} (K)	88.5	67
ΔC (mJ K^{-1} cm^{-3})	11	5
C factor	0.3	0.8
ξ_{ab} (Å)	10.0	13.0
ξ_c (Å)	$\leqslant 0.1$	$\leqslant 0.1$

tal data in Figs. 3(a) and 3(b) indicate sharpening near the parallel field ($\theta=0°$) as Co is doped, implying an increase in anisotropy. In some thicker samples, we have observed a double minimum near the parallel field, which was probably caused by the slightly misaligned domain structure. To avoid such an artifact, we carefully cleaved samples to ≈ 0.01 mm thickness before the transport measurements. The scaling of ρ_a as a function of the reduced field $B_{\rm red}$ gives $\gamma=100\pm 10$ and $=220\pm 10$ for the pure and Co 4% doped sample, respectively. Consequently, we did not observe any impurity-induced reduction of the anisotropy, which was expected in anisotropic 3D systems. Instead, we observed an increase in anisotropy $\gamma=\xi_{ab}/\xi_c$ in the superconducting state. According to the 2D LD model (Josephson-coupled superconductivity),[8] $\xi_c=\xi_{ab}(m_{ab}/m_c)^{1/2}\propto \xi_{ab}t_\perp^{1/2}$, where $t_\perp$ is the interlayer coupling constant. Thus, the observed impurity induced increase in anisotropy by 2.2 times that of the pure sample means the decrease in $t_\perp$ by $(2.2)^{-2}\approx 0.21$ times that of the pure sample.

Figure 4 shows the temperature dependence of out-of-plane resistivity ρ_c for pure and Co 4% doped single-crystal $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$. The two ρ_c curves for Co-doped samples show typical sample dependence for ρ_c measurement. Our early data on ρ_c for the Co-doped sample was scattered from sample to sample. Since the out-of-plane properties are very sensitive to the oxygen content, this is considered to be caused by an oxygen inhomogeneity in the sample during cooling. To eliminate the ambiguity in the oxygen content, we improved the annealing process; the equilibrium oxygen pressures are maintained down to sufficiently low temperature ($\approx$300 °C). Thus we obtained reliable data on ρ_c for the Co-doped samples, as shown in Fig. 4.

Because all the values of ρ_c far exceed Mott's limit ($\approx 10^{-2}$ Ωcm),[15] the out-of-plane conduction can be considered as a tunneling mechanism, $\rho_c \propto (N_0 t_\perp)^{-1}$, where N_0 is the in-plane density of states. The observed impurity induced change in ρ_c could then be attributed to the change in the $t_\perp$ or the N_0. It is natural to consider that the increase in ρ_c is directly related to the increase in γ. Actually, if all of the increase in ρ_c at just above T_c is assumed to come from the reduction in $t_\perp$, $t_\perp^{\rm pure}/t_\perp^{\rm Co}\cong \rho_c^{\rm Co}(T_c^{\rm Co})/\rho_c^{\rm pure}(T_c^{\rm pure})\cong 4.6$, we can well explain the increase in γ, $(\gamma^{\rm Co}/\gamma^{\rm pure})^2\cong 4.8$, within the simple LD model framework. However, this assumption imposes strong temperature dependence on $t_\perp$ as seen in $\rho_c(T)$. Since $t_\perp$, which is determined by the tunneling barrier height and width, does not, in general, strongly depend on temperature, the strong temperature dependence would arise from the dynamical effect.

There are some models attempting to explain ''semiconductive'' behavior of ρ_c with temperature independent $t_\perp$.[16,17] For example, Ioffe *et al.* have proposed that, in the extreme 2D system, the suppression of the N_0 caused by the superconductive fluctuation effect leads to an increase in ρ_c.[17] According to the theory, the density of states fluctuation contribution $\sigma_{\rm DS}^{\perp(2D)}$ to the out-of-plane conductivity is expressed in a wide range of temperatures ($t_\perp^2/T_c \leqslant T-T_c \ll T_c$) as $\sigma_{\rm DS}^{\perp(2D)}\propto -\ln[T_c/(T-T_c)]$. Other superconductive fluctuation contributions (AL or Maki-Thompson type) can be neglected except for around temperatures in the very vicinity of T_c ($T_c\leqslant T\leqslant t_\perp^2/T_c$) when the system is extreme 2D ($t_\perp \ll 1$). We analyzed our experimental data on ρ_c in Fig. 4 using the above functional form of $\sigma_{\rm DS}^{\perp(2D)}$ to test the theory. In the analysis, out-of-plane resistivity, when there are no superconductive fluctuation effects, ρ_{c0}, was simply assumed to be a linear extraporation of the ρ_c at high temperatures. The ρ_c of the pure sample was approximately reproduced as in Ref. 18, while the fitting failed for that of the Co-doped one because the temperature dependence was apparently weaker than the theoretical prediction. Thus, at least, all of the increase in ρ_c near T_c cannot be attributed to the standard superconductive fluctuation effect,

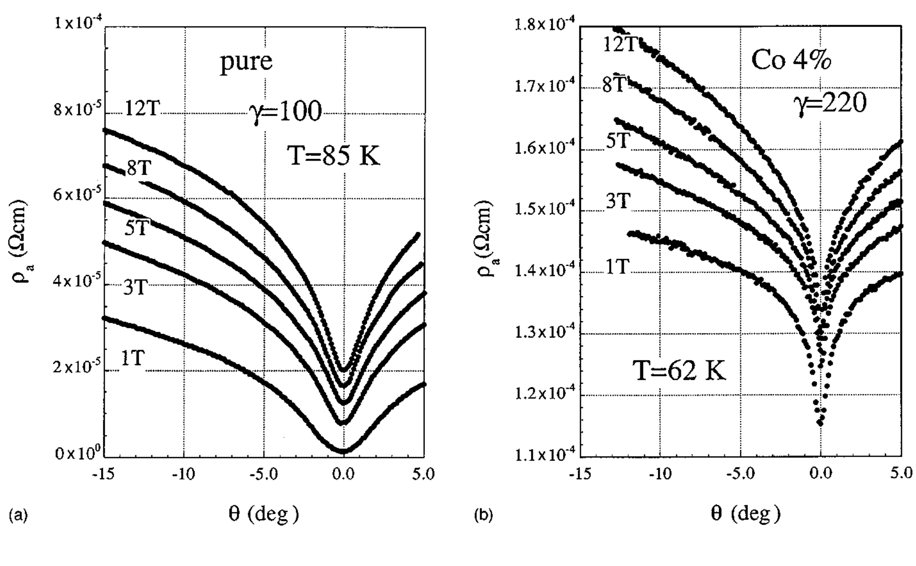

FIG. 3. In-plane resistivity ρ_a at a constant temperature for $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ single crystals when (a) $x=0$ and (b) $x=0.04$ as a function of magnetic field angle with respect to the ab plane. Data are for a different set of samples and a different annealing process. However, the samples have in-plane properties similar to those of Fig. 1.

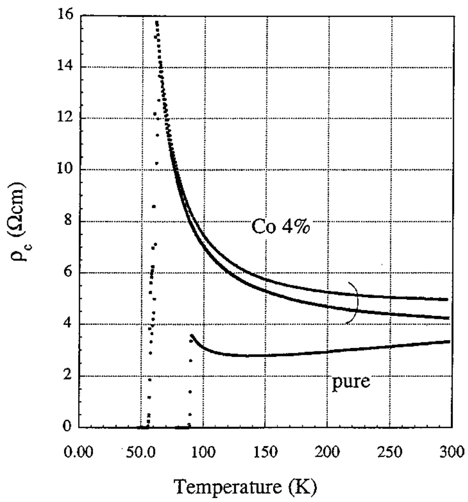

FIG. 4. Out-of-plane resistivities ρ_c of $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ ($x=0,0.04$) single crystals versus temperature. The data for two samples were shown for the Co doped ones.

in which the value of $2\Delta/k_BT_c$ holds constant. Consequently, it seems that there is no hope to explain our impurity effect on γ and ρ_c without recourse to temperature dependent $t_\perp$.

A promising idea is that the $t_\perp$ effectively becomes small as temperature is reduced to T_c due to in-plane charge dynamics (e.g., spin gap) in the strongly correlated 2D system.[4] We must remember, however, that the samples examined here are in the overdoped region. Therefore, the simple ''spin gap scenario'' cannot be applied to this $Bi_2Sr_2CaCu_2O_{8+\delta}$ system. The non-Fermi liquid nature may govern the system in a wide range of hole doping levels. Another interesting point is that the anisotropy seems to be ''frozen'' at T_c. Although our anisotropy measurements cannot go far inside the T_c, $(T-T_c)\leqslant 5$ K, γ seems unchanged below T_c. Some other measurements (e.g., the London penetration depth λ_L)[19] also support this idea. In any case, we would like to emphasize that we must take into account the temperature dependence of $t_\perp$ in the normal state to explain the anisotropy change in the superconducting state caused by the Co doping.

There are two conceivable reasons for the impurity-induced reduction of the $t_\perp$. One is the decrease in the hole doping level due to the trivalent Co substitution for Cu. This accounts for the overall increase (decrease) in the $\rho_c(t_\perp)$ in the measured temperature region. However, this does not explain all the observed increase in γ, if T_c is assumed to be unchanged. The other originates from the decrease in T_c with impurity doping. As the temperature dependence is very strong around T_c, the $\rho_c(t_\perp)$ just above T_c further increased (decreased), accounting for the observed increase in γ.

In conclusion, single crystals of $Bi_2Sr_2Ca(Cu_{1-x}Co_x)_2O_{8+\delta}$ ($x=0,0.04$) were grown by the TSFZ method and their anisotropic transport properties (ρ_a,ρ_c, in-plane resistive transition under the magnetic field, and in-plane resistivity as a function of the magnetic field direction) were examined in the slightly overdoped region. With Co doping, an increase in the anisotropic coherence length ratio $\gamma=\xi_{ab}/\xi_c$ as well as an increase in ρ_c were observed, while, primarily, constant residual resistivity was added to ρ_a. We have confirmed the electronic 2D nature (incoherent interlayer charge transport) of the $Bi_2Sr_2CaCu_2O_{8+\delta}$ system, because the results follow the 2D Lawrence-Doniach model quantitatively when the interlayer coupling $t_\perp$ is defined at just above T_c. The analysis also showed that the origin of the ''semiconductive'' ρ_c lay in the temperature dependence of $t_\perp$, which would restrict the model for the interlayer charge transport in the high-T_c cuprates.

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