In-plane and out-of-plane magnetoresistance in $La_{2-x}Sr_xCuO_4$ single crystals

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The magnetoresistance of $La_{2-x}Sr_xCuO_4$ single crystals has been studied extensively over a wide composition range ($0.07 \leqslant x \leqslant 0.28$) using current parallel (in plane) and perpendicular (out of plane) to the CuO_2 plane. In the underdoped superconducting phase ($x \sim 0.10$), the in-plane magnetoconductivity above T_c is well described as fluctuation conductivity but only with the Aslamasov-Larkin term. The negligibly small Maki-Thompson contribution is suggestive of anisotropic Cooper pairing. We find a pronounced negative and isotropic out-of-plane magnetoresistance at low temperatures in this composition range. In the optimally doped to the overdoped superconducting phases ($0.15 \leqslant x \leqslant 0.20$), a substantial normal-state component is observed in the in-plane magnetoresistance. The classical Kohler's rule appears to break down for the normal-state magnetoresistance, which supports the involvement of two distinct scattering rates τ_{tr} and τ_H. In the out-of-plane magnetoresistance, we find an unconventional scaling $\Delta\rho_c/\rho_c \propto (H/\rho_a)^2$ for $H \perp J$ and $(H/T)^2$ for $H \parallel J$. In contrast to these anomalous behaviors, we find that Kohler's rule holds for both the in-plane and the out-of-plane transverse magnetoresistance in the overdoped normal metal region, implying a conventional anisotropic three-dimensional transport. These findings provide further evidence for the unconventional normal-state transport in the samples which exhibit high-T_c superconductivity.

I. INTRODUCTION

One of the most interesting and puzzling issues in the research of high-T_c superconductors is the anomalous normal-state transport properties.[1–3] High-T_c cuprates show a number of distinctive transport properties, which is hard to explain in terms of conventional Fermi liquid theory for metals. In the optimally doped compounds, the T-linear in-plane resistivity over a wide temperature range and the ω-linear scattering rate $1/\tau$, deduced from the optical measurements, are commonly observed, which contrast with what is expected for the conventional Fermi liquid, $1/\tau \propto \omega^2$. The Hall effect, indicative of a small number of carriers, appears to violate the Luttinger sum rule which requires a large Fermi surface containing ~ 1 electron/Cu. In addition, the Hall effect is known to be strongly temperature dependent; for instance, $R_H \propto 1/T$ for $YBa_2Cu_3O_7$ (YBCO). The out-of-plane resistivity shows a semiconducting temperature dependence in contrast to the metallic in-plane resistivity, suggesting that the conduction mechanism along the c axis is completely different from that along the ab plane.

High-T_c cuprates can be viewed as a doped charge-transfer insulator. As a function of carrier doping, the system generally changes from antiferromagnetic insulator to superconductor to normal metal. The anomalous transport can be seen only in the vicinity of charge-transfer insulator-to-metal transition, suggestive of a close link between the anomalous charge transport and the strong electron correlation. In the overdoped normal metal region where superconductivity disappears, the transport properties recover much more conventional behavior. For example, the in-plane resistivity exhibits a T^2-like temperature dependence.[4] The out-of-plane resistivity shows almost the same temperature dependence as the in-plane resistivity, indicating a crossover from two dimensions (2D) to 3D.[5]

To get further insight into the anomalous charge transport, the magnetoresistance (MR) measurement is a useful tool since it is more sensitive to the change in the charge carrier scattering rate $1/\tau$, effective mass m^*, and the geometry of the Fermi surface. In conventional metals, the electrical conductivity can be described in terms of the Boltzmann equation.[6] In the presence of a magnetic field H, the change in the distribution function $g(\mathbf{v})$ is described by

$$g(\mathbf{v}) = \left[1 + (H\tau)\frac{\mathbf{e}}{c}\mathbf{v}\times\hat{\mathbf{H}}\cdot\frac{\partial v}{\hbar\,\partial\mathbf{k}}\cdot\frac{\partial}{\partial\mathbf{v}}\right]^{-1}\left[-\tau\mathbf{e}\mathbf{E}\cdot\mathbf{v}\frac{\partial f^0}{\partial\varepsilon}\right]. \tag{1}$$

The magnitude of the magnetic field contributes to Eq. (1) in a product of H and τ. Since $1/\tau$ is generally proportional to the zero-field resistivity ρ_0, the MR $\Delta\rho/\rho_0$ depends only on H/ρ_0. This results in a scaling law referred to as Kohler's rule which holds in many conventional metals,

$$\frac{\Delta\rho}{\rho_0}=f(H\tau)=F\left(\frac{H}{\rho_0}\right). \quad (2)$$

In the low-field limit, the MR quadratically depends on H, and is therefore scaled as $\Delta\rho(T)/\rho_0(T)=\text{const}\times(H/\rho_0)^2$.

Although the in-plane MR of high-T_c cuprates in the normal state has already been studied by several groups, the experimental results reported so far are controversial. Lacerda *et al.*[7] found a positive transverse in-plane MR in underdoped $La_{1.925}Sr_{0.075}CuO_{4+\delta}$, which follows Kohler's rule. They interpreted their results using a semiphenomenological theory based on anisotropic scattering on the hole-pocket Fermi surfaces. In contrast, Preyer *et al.*[8] observed a negative and isotropic in-plane MR in underdoped $La_{2-x}Sr_xCuO_4$.

Recently, Harris *et al.*[9] reported that, in both 90 K and 60 K $YBa_2Cu_3O_{7-\delta}$, the transverse in-plane MR is scaled by $\Delta\rho(T)/\rho_0(T)\propto(H^2/T^4)$. Taking account of $1/\tau\propto T$, as expected from the T-linear resistivity, the observed MR apparently violates Kohler's rule. They interpreted their result in terms of the two distinct scattering rates $\tau_{\text{tr}}\propto T$ and $\tau_H\propto T^2$ which they had pointed out previously, based on Hall angle measurements. They also observed an analogous violation of Kohler's rule in optimally doped $La_{2-x}Sr_xCuO_4$.

Only a few studies have been performed on the out-of-plane MR, apparently due to the lack of single crystals, with a large dimension along the c axis. Yan *et al.*[10] studied the out-of-plane MR in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO), and observed a negative MR, which rapidly increases in magnitude with decreasing temperature. The temperature dependence of the magnitude can be described by the activation law $\exp(-U_L/T)$, with a gap U_L that varies with the oxygen content δ. Since the negative MR was only weakly dependent on the field direction, they claimed that the spin degrees were primarily responsible for creating the barrier to interplane charge transport in the bilayer cuprates.

The apparent discrepancies above suggest to us that the behaviors of MR could be largely dependent on the carrier concentration and/or on the sample inhomogeneity, and therefore motivate us to perform extensive measurements over a wide hole concentration range using high-quality specimens.

The $La_{2-x}Sr_xCuO_4$ (LSCO) system has been regarded as a prototype of high-T_c cuprates because of its simple crystal structure consisting of a single CuO_2 plane and of its chemical flexibility against hole doping. Notably, this system is one of a few systems which cover the full range of compositions from under- to overdoped superconductivity as well as nonsuperconductivity phases. Because of the advantages, much experimental data have been accumulated for LSCO as a function of hole doping. Recent progress in the crystal-growth technique has enabled us to perform reliable transport measurements using single crystals, over a wide range of Sr doping which covers the full generic phase diagram.[11] In this paper, we report the in-plane and out-of-plane MR $\Delta\rho/\rho_0$ of LSCO single crystals as a function of temperature, magnetic field, and the doping level.

II. EXPERIMENTAL DETAILS

A series of $La_{2-x}Sr_xCuO_4$ single crystals with various Sr contents ($0.07\leqslant x\leqslant 0.28$) was grown by the traveling solvent floating zone technique as reported previously.[11] All the crystals had a large dimension (~5 mm) along the c axis, enough for direct measurements of c-axis transport. The Sr concentration was determined by inductively coupled plasma (ICP) spectroscopy. The μm range homogeneity of Sr concentration x was checked by an electron probe microanalyzer (EPMA). $\Delta x<0.005$ in the underdoped samples ($x<0.15$), and $\Delta x<0.01$ in the overdoped samples ($x\geqslant 0.15$). Observation of the polished cross section of the crystalline-grown rods by a polarized microscope and by the x-ray back-reflection Laue technique confirmed that a substantial portion of each of the grown rods consisted of a single-crystalline domain. The grown crystals were carefully cut out into rectangular slab specimens along the main crystalline axes with an accuracy of 1°–2°. Sample dimensions for the transport measurements were typically $3\times1\times0.2$ mm^3, with the longest axes both parallel and perpendicular to the CuO_2 plane for the in-plane and out-of-plane measurements, respectively. The specimens were then annealed at about 800 °C under 1 atm of pure flowing oxygen for 3 days to 1 week. With increasing doping, the annealing period was set longer since oxygen vacancies are much more easily introduced into overdoped samples than underdoped ones.

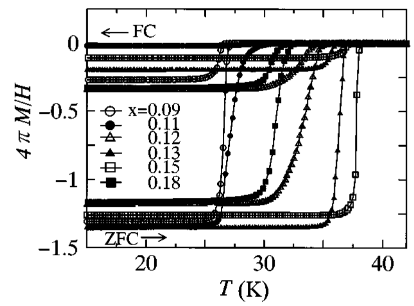

FIG. 1. Temperature dependence of the zero-field-cooled and field-cooled magnetization for $La_{2-x}Sr_xCuO_4$ single crystals with various Sr contents, measured in a magnetic field of 1 Oe parallel to the c axis.

The high quality of the crystals has been confirmed from magnetic shielding and the Meissner measurements under a field of 1 Oe parallel to the c axis, using a superconducting quantum interference device (SQUID) magnetometer. As shown in Fig. 1, the crystals exhibited rather sharp superconducting transitions, with transition width less than 1–2 K, and the magnitude of shielding indicates the perfect diamagnetism (except for the nonsuperconducting overdoped crystal of $x=0.28$).

Both in-plane ($J\|ab$) and out-of-plane ($J\|c$) resistance values of the crystals were measured by the conventional four-probe technique, over a temperature range between 40 K and 200 K under magnetic fields up to 15 T. The out-of-plane resistance was measured by a dc nanovoltmeter, while the measurements of the in-plane resistance were performed with a low-frequency ac resistance bridge (15.9 Hz) due to the lower magnitude of the resistivity. The voltage and the current electrodes were formed by gold paste with a heat treatment at 800 °C for 2–3 h under 1 atm of pure O_2, which allows a contact resistance of less than 1 Ω. The MR measurements were performed by sweeping magnetic fields at fixed temperatures. During the measurements, the tem-

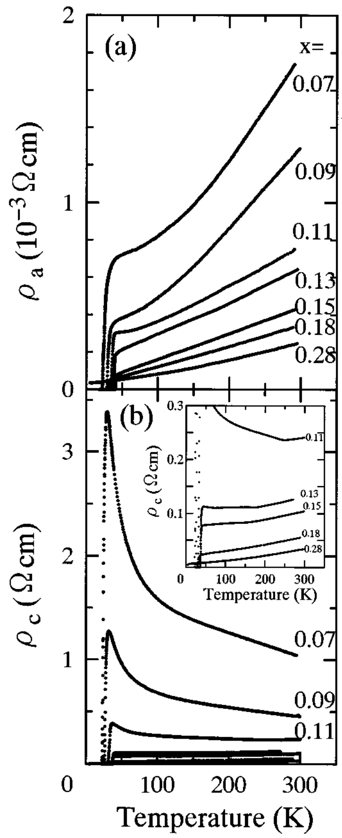

FIG. 2. Temperature dependence of in-plane (a) and out-of-plane (b) resistivity for $La_{2-x}Sr_xCuO_4$ crystals with various Sr contents.

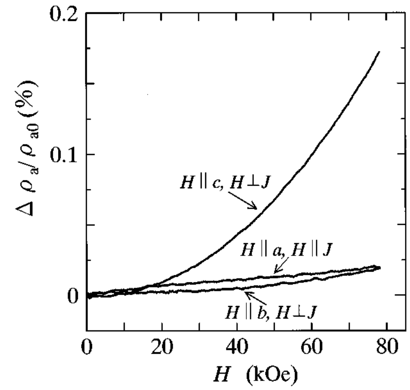

FIG. 3. In-plane ($J\|ab$) magnetoresistance of $La_{2-x}Sr_xCuO_4$ crystal ($x=0.09$) as a function of magnetic field at $T=60$ K, with various field orientations $H\|c$, $H\|J\|ab$, and $H\perp J\|ab$.

perature was stabilized by a resistance thermometer (Lakeshore cernox).

The zero-field in-plane and out-of-plane resistivity values of the crystals used in this study are shown in Fig. 2. The magnitude of ρ_a for the optimally doped $x=0.15$ sample (~ 400 $\mu\Omega$ cm at room temperature) was comparable with the lowest value reported so far for LSCO crystals. While the in-plane resistivity was always metallic ($d\rho_a/dT>0$) over the whole composition range investigated, the out-of-plane resistivities in the underdoped to optimally doped superconducting phase showed semiconducting temperature dependences. In these regions, we found a well-defined kink in each ρ_c-T curve, which coincided well with the structural phase transition temperature from the high-temperature tetragonal to the low-temperature orthorhombic phases. Eventually in the nonsuperconducting overdoped region ($x=0.28$), the temperature dependence of ρ_c was essentially the same as that of ρ_a. Namely, the ratio ρ_c/ρ_a was nearly temperature independent, 50–100, indicative of anisotropic 3D charge transport in this region.

III. RESULTS

A. In-plane magnetoresistance in the overdoped and optimally doped regions

First, we focus on the in-plane MR in the overdoped and optimally doped regions. Figure 3 shows a typical example of the in-plane ($J\|ab$) MR under three different magnetic field orientations: ($H\|ab$,$H\|J$), ($H\|ab$,$H\perp J$), and ($H\|c$,$H\perp J$). An appreciable amount of MR can be seen only for the $H\|c$ configuration, i.e., transverse MR with field parallel to the c axis. The negligibly small longitudinal MR indicates that the orbital part dominates the transverse MR. On the other hand, the finding that the transverse MR with $H\|ab$ is much smaller than that with $H\|c$ implies a strong mass anisotropy between in-plane and out-of-plane directions. The observed anisotropy is qualitatively consistent with other experiments such as the magnitude of resistivity. The dominant orbital contribution for $H\|c$ is observed over the entire temperature range, and is common among to all of the specimens investigated here. In the following, we will discuss only the high-symmetry transverse MR with $H\|c$ as the orbital scattering part.

By extending the MR measurements over a wide temperature range, we can see the validity of the classical Kohler's rule in the overdoped normal metal phase. In Fig. 4(f), the transverse MR is shown for $x=0.28$ at various temperatures. As seen in Fig. 4(f), the MR is always positive and monotonically decreases with increasing temperature. The magnetic field dependences are essentially H^2 up to 80 kOe for all temperatures. The data in Fig. 4(f) are replotted as $\Delta\rho_a/\rho_{a0}$ vs $(H/\rho_{a0})^2$, Kohler's plot, in Fig. 5(a). All the data fall onto a single straight line, which implies that the MR is essentially scaled by H/ρ_{a0}, i.e., that it follows the classical Kohler's rule.

In contrast to the Kohler scaling behavior in the overdoped sample, MR for the superconducting samples cannot be simply scaled by H/ρ_{a0}, as shown in Fig. 5. At high temperatures, the MR curves more or less fall onto the same single line. However, at low temperatures, the MR curves deviate upwards from those at high temperatures. This deviation becomes more significant as the temperature approaches T_c and as the composition approaches $x=0.15$, the optimal composition. This evolution strongly suggests that violation of Kohler's rule in the superconducting samples is largely due to a superconducting fluctuation. Hence, we will analyze this enhancement of MR at low temperatures in terms of the superconducting fluctuation.

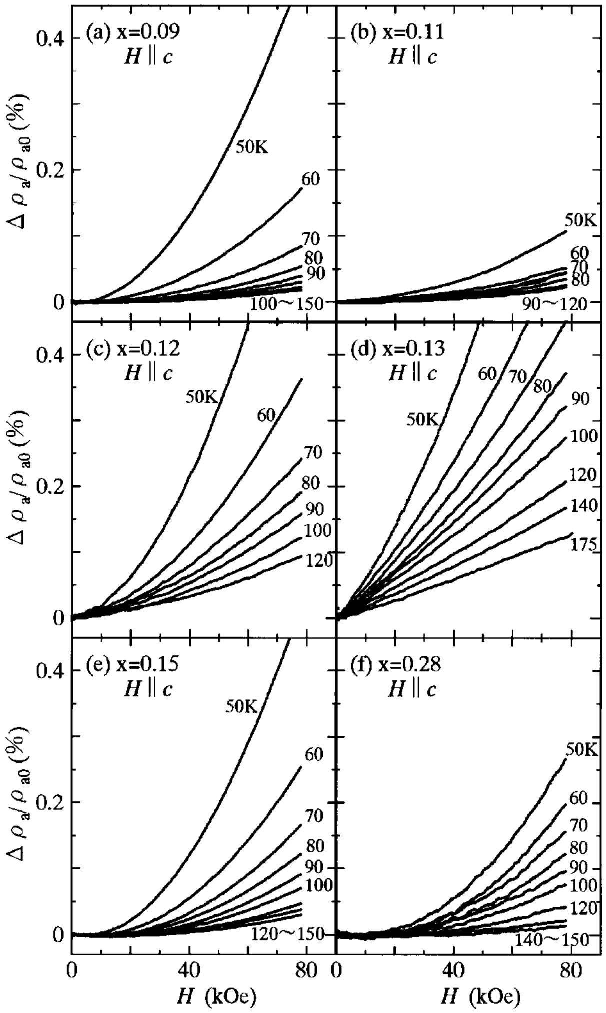

FIG. 4. Transverse ($H \perp J$) in-plane ($J \parallel ab$) magnetoresistance with $H \parallel c$ in $La_{2-x}Sr_xCuO_4$ crystals $x=0.09$* (a), $x=0.11$* (b), $x=0.12$* (c), $x=0.13$* (d), $x=0.15$** (e), and $x=0.28$*** (f), as a function of magnetic field at selected temperatures (* underdoped and superconductivity, ** optimally doped and superconductivity, and *** overdoped and nonsuperconductivity).

B. In-plane magnetoresistance in the underdoped region

In the underdoped superconducting phase, the MR behaves in a much more complicated way. As shown in Fig. 4, the magnitude of the MR in this region does not vary monotonically with hole concentration. First, a pronounced anomaly is observed near $x=0.13$ just below the optimal composition of $x=0.15$, as seen in Fig. 4(d). It is clear from the data above 100 K that an anomalous H-linear behavior is dominant at least up to 80 kOe, which causes the MR to be significantly larger than the other compositions. With approaching T_c, the MR tends to show an upward curvature. The finite slope at zero field, however, indicates the presence of a large H-linear term even at low temperatures. The MR in the vicinity of T_c, therefore, appears to consist of the anomalous H-linear term plus the H^2 term associated with the superconducting fluctuation. The observed singularity around a Sr composition of $x=0.13$ is intrinsic. The results shown in Fig. 4(d) are reproducibly observed for a sample taken from a different batch with the same Sr concentration. Furthermore, the H-linear term is also observed in the vicinity of $x=0.13$, i.e., the $x=0.12$ sample, as seen in Fig. 4(c). This distinct H-linear dependence is not observed for the other samples, as shown in Figs. 4(a) and 4(b). At high temperatures the magnitude of the MR is vanishingly small in the samples with the $x=0.09$ and 0.11. Comparing $x=0.11$ with the $x=0.09$ samples, the H^2-dependent MR is strongly suppressed for the $x=0.11$ sample, which is ascribed to the "1/8 anomaly" composition.

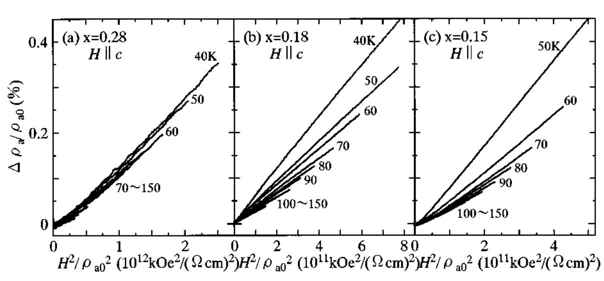

FIG. 5. Kohler plots for the crystals of $x=0.28$ (a), 0.18 (b), and 0.15 (c), at selected temperatures. The presence of a universal line for $x=0.28$ implies that Kohler's rule holds.

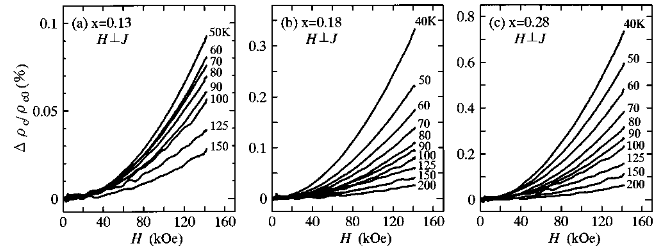

FIG. 6. Transverse ($H \perp J$) out-of-plane ($J \parallel c$) magnetoresistance in $La_{2-x}Sr_xCuO_4$ crystals of $x=0.13$ (a), $x=0.18$ (b), and $x=0.28$ (c), as a function of magnetic field at selected temperatures.

C. Out-of-plane magnetoresistance in the overdoped and optimally doped regions

Let us turn to the out-of-plane MR. Figure 6 displays the transverse ($H \parallel ab \perp J$) out-of-plane MR for $x=0.13$, 0.18, and 0.28 samples. We find that, in these samples, the out-of-plane MR is always positive, that it has an H^2 dependence, and that it monotonically decreases with increasing temperature, similar to the in-plane MR. (It is noted that the anomalous out-of-plane MR is not observed in the $x=0.13$ sample which shows an anomalous in-plane MR.)

One of the most remarkable findings is an anomalous scaling of out-of-plane MR. In Fig. 7, we replot the transverse out-of-plane MR as a function of $(H/\rho_{a0})^2$, not $(H/\rho_{c0})^2$. It is seen that $\Delta\rho_c/\rho_{c0}$ against $(H/\rho_{a0})^2$ falls on a single straight line over a wide temperature range, for $x=0.18$ and $x=0.28$ samples. It is not surprising that the MR for $x=0.28$ is scaled by ρ_a. In the overdoped normal metal, the temperature dependence of ρ_c is essentially the same as that of ρ_a. The scaling by (H/ρ_{a0}) for $x=0.28$ therefore implies Kohler's rule. For the $x=0.18$ sample, however, the temperature dependence of ρ_c is different from that of ρ_a. Therefore, the scaling by (H/ρ_{a0}) observed here cannot be

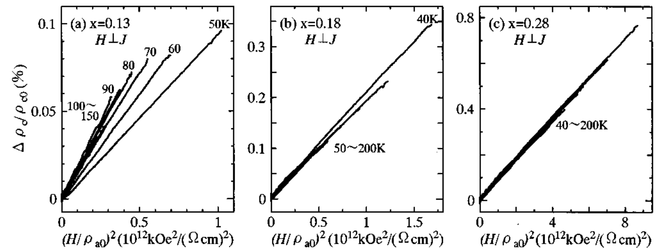

FIG. 7. Transverse ($H \perp J$) out-of-plane ($J \| c$) magnetoresistance in $La_{2-x}Sr_xCuO_4$ crystals of $x = 0.13$ (a), $x = 0.18$ (b), and $x = 0.28$ (c), as a function of $(H/\rho_{a0})^2$ at selected temperatures. Note that the field dependence is scaled by the in-plane resistivity ρ_{a0}. If we assume that Kohler's rule is valid for the anisotropic materials, its validity gives the same gradient at each temperature.

understood by conventional Kohler scaling (H/ρ_{c0}). In Fig. 7(a) a similar scaling is also observed in the slightly underdoped sample ($x = 0.13$), at least at high temperatures. The downward deviation seen at low temperatures might be attributed to the onset of negative MR seen in the underdoped region. The scaling $(H/\rho_{a0})^2$ suggests that the out-of-plane MR for the optimally doped to overdoped superconducting phases is dominated essentially by the in-plane scattering rate $1/\tau_a$.

Another interesting observation is that, in contrast to the observations reported in conventional two-dimensional compounds such as an intercalated graphite, the longitudinal MR is larger than the transverse MR (Fig. 8). Furthermore, in the $x = 0.13$ and $x = 0.18$ samples for which the transverse MR is scaled by (H/ρ_{a0}), the longitudinal MR is essentially scaled by (H/T) as shown in Fig. 9, which implies that the Zeeman energy plays a substantial role in the longitudinal MR.[12]

D. Out-of-plane magnetoresistance in the underdoped region

In the underdoped sample with $x = 0.09$ which shows a strong semiconducting temperature dependence of ρ_c, a distinct negative and isotropic MR has been observed at low temperatures, unlike optimally doped to overdoped samples. As shown in Fig. 10(a), the transverse MR is virtually absent at high temperatures. Below about 90 K, a distinct negative MR is observed which appears to be almost isotropic. As seen in Fig. 10(b), the longitudinal MR is clearly negative at

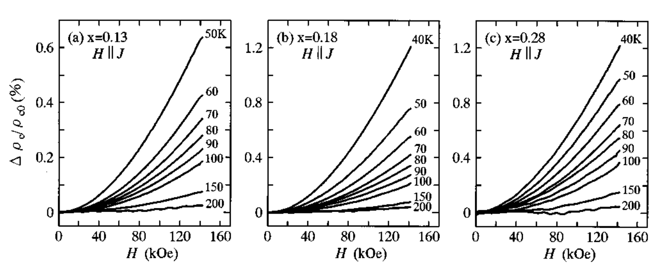

FIG. 8. Longitudinal ($H \| J$) out-of-plane ($J \| c$) magnetoresistance in $La_{2-x}Sr_xCuO_4$ crystals of $x = 0.13$ (a), $x = 0.18$ (b), and $x = 0.28$ (c), as a function of magnetic field.

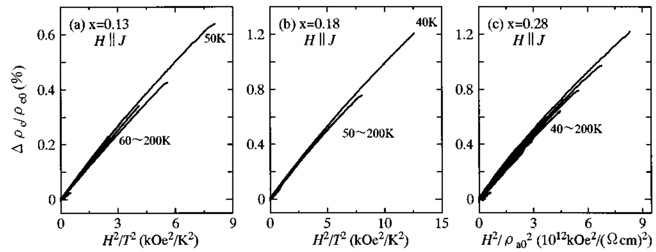

FIG. 9. Longitudinal ($H \| J$) out-of-plane ($J \| c$) magnetoresistance in $La_{2-x}Sr_xCuO_4$ crystals of $x = 0.13$ (a) and $x = 0.18$ (b) as a function of $(H/T)^2$, and $x = 0.28$ (c) as a function of $(H/\rho_{a0})^2$.

50 K, with magnitude comparable with that of transverse MR. At high temperatures around 100 K, the longitudinal MR becomes positive, with a magnitude much larger than that for the transverse MR. At 40 K, we can see a rather complicated field dependence in Fig. 10(b), which is likely due to the coexistence of the negative component and the superconducting fluctuation contribution. A similar negative MR is also observed in the $x = 0.07$ underdoped sample. This isotropic and negative MR implies that a spin part, rather than a orbital part, plays a significant role in the negative out-of-plane MR.

IV. DISCUSSION

A. Superconducting fluctuations

In the previous section, we have shown the breakdown of the scaling by (H/ρ) for the transverse in-plane MR, which becomes particularly significant in underdoped samples. The observed systematics implies that superconducting fluctuations play a significant role in the breakdown. In layered high-T_c cuprates, factors such as high transition temperature, short coherence length, and quasi-two-dimensionality substantially increase the influence of the superconducting fluctuations on the conductivity compared with conventional superconductors. In this section, we estimate the contribution from the superconducting fluctuations to estimate the contribution from the normal-state resistivity. In the next section,

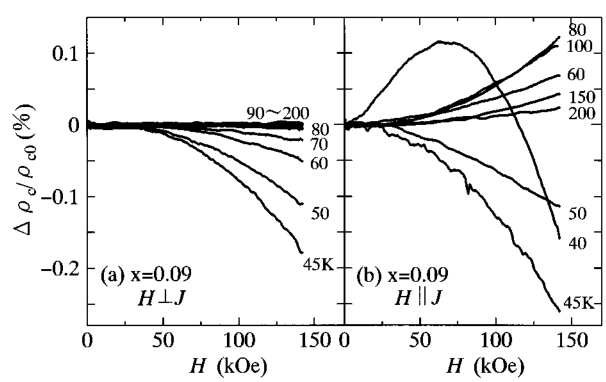

FIG. 10. Transverse (a) and longitudinal (b) out-of-plane magnetoresistance in underdoped $La_{2-x}Sr_xCuO_4$ crystals of $x = 0.09$, as a function of magnetic field. Negative and isotropic magnetoresistance is observed at low temperatures.

we discuss the possible violations of Kohler's rule after properly subtracting the fluctuation contribution.

The excess conductivity induced by the superconducting fluctuation consists of an Aslamasov-Larkin (AL) type contribution, which is associated with fluctuational Cooper pairs, and the Maki-Thompson (MT) type contribution which arises from the interaction of electrons with fluctuational Cooper pairs. The fluctuation conductivity in a magnetic field, $\Delta\sigma(H)$, comprises four contributions: the AL-orbital (ALO), MT-orbital (MTO), AL-Zeeman (ALZ), and MT-Zeeman (MTZ) contributions. The total field-dependent fluctuation conductivity $\Delta\sigma(H)_{\mathrm{total}}$ is the sum of the four contributions

$$\Delta\sigma_{\mathrm{total}}(H)=\Delta\sigma_{\mathrm{ALO}}(H)+\Delta\sigma_{\mathrm{MTO}}(H)+\Delta\sigma_{\mathrm{ALZ}}(H)+\Delta\sigma_{\mathrm{MTZ}}(H). \quad (3)$$

Each term of this equation has been given by Hikami and co-workers[13,14] for the dirty limit form and by Bieri *et al.*[15] for the clean limit form.

So far, several groups[16–21] have investigated the magnetoconductivity of high-T_c cuprates in terms of the superconducting fluctuations. They have fitted the obtained MR data to the sum of the above four contributions. Most of their results indicated that the MT term significantly contributes to the fluctuation conductivity. A conflicting result has been obtained by Semba *et al.*, concluding that the MTZ term was negligible.[19]

Whether the MT term is present or not in fluctuation conductivity offers a unique opportunity to examine the symmetry of Cooper pairs in high-T_c cuprates. Yip[22] has shown theoretically that, in superconductivity with anisotropic pairing, the MT contribution should not be present while the AL contribution is essentially unchanged. In this context, the presence of the MT term in most of the previous works implies that high-T_c cuprates may be conventional s-wave superconductors.

We have analyzed the present data in terms of fluctuation conductivity, using the dirty limit form for the underdoped sample and using the clean limit form for the overdoped sample. Regarding the superconducting parameters $\xi_{ab}(0)$ and $\xi_c(0)$ of the present LSCO single crystals, it has been previously reported that $\xi_{ab}(0)$ is almost constant ($\sim$30 Å) with doping, while $\xi_c(0)$ decreases with increasing doping.[23,24] From $\sigma=h/e^2(k_F l)$, under the assumption of a small Fermi surface with carrier concentration $n\sim x$, we estimate that the mean free path $l\sim26$ Å for $x=0.09$, $l\sim64$ Å for $x=0.15$, and $l\sim80$ Å for $x=0.18$ samples. In the underdoped sample, l is comparable with $\xi_{ab}(0)$, suggestive of the intermediate region. With increasing doping, l rapidly increases and the overdoped sample approaches a clean limit superconductor. In the following discussion, however, it is not crucial whether the data are analyzed by the clean or the dirty limit form. The dephasing time τ_ϕ is assumed to have the same temperature dependence as τ_{tr}.

In Fig. 11, we plot the results of the calculation and the experimental data for $x=0.09$ (underdoped), $x=0.15$ (optimally doped), and $x=0.18$ (overdoped) samples. First, we focus on the underdoped $x=0.09$ sample. Figure 11(a) clearly shows that the magnetoconductivity in the $x=0.09$ sample is well described only by the AL contribution over a wide temperature range. The fitting parameters $\xi_{ab}(0)$, $\xi_c(0)$, and T_c, using only the AL term, well agree with those reported by other experimental techniques. The MT contribution to the magnetoconductivity therefore should be substantially smaller than the AL term. To obtain a good fit to the results using both AL and MT terms, an extremely small value of τ_ϕ (e.g., $<\sim10^{-15}$ s at 40 K) must be introduced, which appears unrealistic because $\hbar/\tau_\phi \geqslant 10^3$ K. Therefore we conclude that the MT contribution is absent in underdoped LSCO. In view of the prediction by Yip,[22] the absence of the MT term suggests that underdoped LSCO is a superconductor with non-s-wave pairing. Recently, experiments such as Raman spectroscopy[25] and neutron scattering[26] have been interpreted to support the existence of an anisotropic nodal (extended s- or d-wave) gap in LSCO. The results are consistent with the present interpretation of the fluctuation conductivity results.

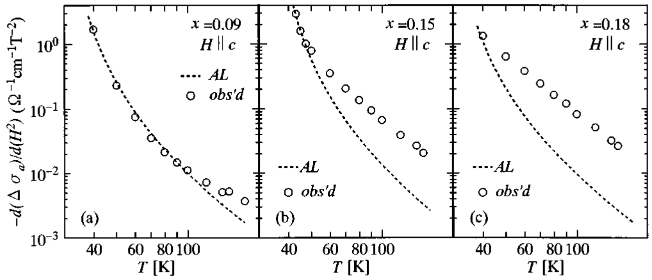

FIG. 11. Temperature dependence of $-d(\Delta\sigma_a)/d(H^2)$ for $La_{2-x}Sr_xCuO_4$ crystals with (a) $x=0.09$ and (b) $x=0.18$. Open circles indicate the experimental data and solid curves show the calculated AL contribution. The fitting parameters used for the broken lines are for (a) $x=0.09$, $T_c=29.2$ K, $\xi_c(0)=0.75$ Å, $\xi_{ab}(0)=30$ Å, for (b) $x=0.15$, $T_c=35$ K, $\xi_c(0)=1.4$ Å, $\xi_{ab}(0)=28$ Å, and for (c) $x=0.18$, $T_c=30$ K, $\xi_c(0)=1.9$ Å, $\xi_{ab}(0)=30$ Å.

As seen in Figs. 11(b) and 11(c), in the optimally doped and overdoped regions, one can see a weak temperature dependence and appreciable upward deviation of the experimental data from the calculated data by AL terms at high temperatures, unlike in the underdoped samples. However, even if we take account of the contributions of both AL and MT terms in any theory, the temperature dependence observed cannot be reproduced. In previous reports, it has been assumed that MR in the normal state arises only from superconducting fluctuations. However, considering that the MR in the nonsuperconducting sample of $x=0.28$ is comparable, we strongly believe that the normal-state MR cannot be neglected. Applying the above discussion to the underdoped region, we assume that only the AL term contributes to the magnetoconductivity due to the superconducting fluctuations, and that the rest originates from the normal-state MR.

B. Violation of Kohler's rule

With the substantial contribution from the superconducting fluctuations in mind, we address the normal-state MR in terms of the violation of Kohler's rule, the issue raised in the context of the T^2 dependence of the Hall angle. Chien *et al.*[27] have reported that the T^2 dependence of the Hall angle,

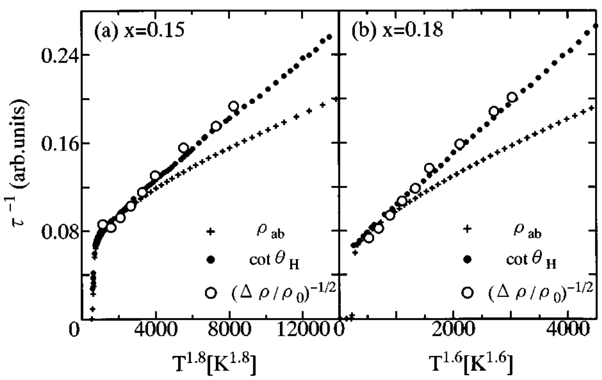

FIG. 12. Temperature dependences of $\rho_{ab}\sim\tau_{tr}^{-1}$, $\cot\theta_H\sim\tau_H^{-1}$, and $(\Delta\rho/\rho_0)^{-1/2}\sim\tau_{MR}^{-1}$ for $x=0.15$ and $x=0.18$ samples. τ_{MR} shows essentially the same temperature dependence as τ_H, not τ_{tr}.

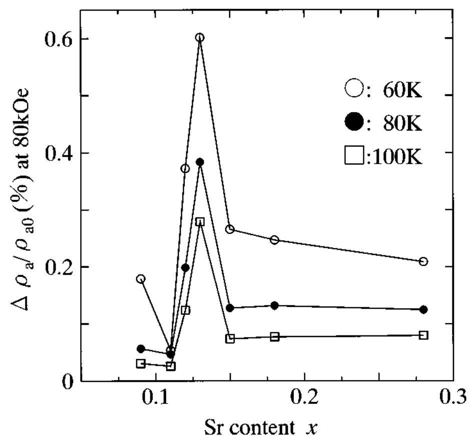

FIG. 13. Sr composition dependence of the in-plane magnetoresistance at 80 kOe at selected temperatures. Note the presence of two singular compositions $x=0.11$ and $x=0.13$.

$\cot\theta_H=\alpha T^2+\beta$, is commonly observed in a series of Zn-doped YBCO single crystals. The result was interpreted by introducing two distinct scattering rates $\tau_{tr}^{-1}\propto\rho\propto T$ and $\tau_H^{-1}\propto\cot\theta_H\propto T^2$. Since then, the T^2 dependence of the Hall angle was confirmed in a variety of high-T_c cuprates.[28–30] As given in Eq. (2), Kohler's rule in the framework of the Boltzmann equation is based on an isotropic scattering process. If the temperature dependence of τ_H^{-1} is clearly different from τ_{tr}^{-1}, which dominates in determining resistivity, Kohler's rule should then be violated since the orbital MR is closely related with the *Hall* scattering.

Since the above analysis indicates that the normal-state contribution is dominant only in the overdoped region, we focus on the optimally doped and the overdoped regions to examine the possible violation of Kohler's rule. In Fig. 12, we plot the temperature dependences of scattering rates τ_{tr}^{-1}, τ_H^{-1}, and τ_{MR}^{-1}, deduced from ρ, $\cot\theta_H$, and $\Delta\rho/\rho_0$ respectively, for $x=0.15$ and $x=0.18$ samples. Within the Boltzmann equation approach, the resistivity is connected with τ as $\rho\sim\tau_{tr}^{-1}$ and the Hall angle as $\cot\theta_H\sim\tau_H^{-1}$. As given in Eq. (2), when the MR quadratically depends on H, $\Delta\rho/\rho_0\sim(H\tau)^2$, then $(\Delta\rho/\rho_0)^{1/2}$ at a fixed field is proportional to τ_{MR}. Here we have subtracted the AL contribution from the obtained magnetoconductivity, using the above analysis. As indicated from the linear behavior in Fig. 12, the temperature dependence of τ_H^{-1} is well described in terms of the power law $AT^{1.8}+B$ for the $x=0.15$ sample and $A'T^{1.6}+B'$ for the $x=0.18$ sample. In contrast, τ_{tr}^{-1} is almost T linear in these samples, and therefore, the line for τ_{tr}^{-1} is convex in Fig. 12, indicating a distinctly different temperature dependence from τ_H^{-1}. By plotting τ_{MR}^{-1} deduced from the MR data in Fig. 12, it is clear that $(\Delta\rho/\rho_0)^{-1/2}\sim\tau_{MR}^{-1}$ shows the same temperature dependence as $\cot\theta_H\sim\tau_H^{-1}$, but different from $\rho\sim\tau_{tr}^{-1}$, which is consistent with the assumption of two distinct scattering rates as claimed by Harris *et al.*[9]

In Fig. 12, we find that the temperature dependence of τ_H^{-1} deduced from MR and $\cot\theta_H$ changes from a $T^{\sim 2}$ dependence to a weaker power law in the optimally doped to overdoped regions ($T^{1.8}$ for $x=0.15$ and $T^{1.6}$ for $x=0.18$). τ_{tr}^{-1} is known to change from T linear to a stronger power law with increasing doping.[4] The difference between τ_H^{-1} and τ_{tr}^{-1} is therefore getting substantially smaller as the composition approaches the overdoped normal metal region. In the overdoped normal metal where τ_{tr}^{-1} is roughly $\sim T^{1.5}$, Kohler's rule holds well. This means that τ_{tr}^{-1} and τ_{MR}^{-1} eventually show the same temperature dependence,[31] in proportion to $\sim T^{1.5}$. In this regards, the disappearance of superconductivity on increasing the doping level is associated with the crossover from the anomalous metal phase with two distinct scattering rates to the conventional metal with a universal τ.

C. Two singular compositions $x=0.11$ and $x=0.13$

The systematic evolution of the MR as a function of doping is summarized in Fig. 13. The figure clearly illustrates a pronounced anomaly at $x=0.11$ (dip) and 0.13 (peak), as described in the previous section. We ascribe the suppression of low-temperature MR near $x=0.11$ to the "1/8 anomaly" which is firmly established in the La214 system. Around the hole concentration with $p=1/8$, the superconductivity is known to be suppressed by the charge ordering and/or structural lattice instability against a low-temperature tetragonal phase.[32–34] Recently several groups claimed that the suppression of superconductivity for LSCO occurs around $x=0.115$ rather than $0.125=1/8$.[35,36] In the present series of single crystals, the suppression of superconductivity is indeed most pronounced for the $x=0.11$ sample (see Fig. 1). This is exactly the composition where we observe the suppression of the low-temperature MR. The correlation between superconductivity and the magnitude of MR provides strong evidence for the dominant superconducting fluctuations in the underdoped region.

At this stage, we cannot explain the anomaly in the specimen with $x=0.13$. We speculate on the following two possibilities. One is related to the 1/8 anomaly. As stated above, the suppression of superconductivity is most pronounced at $x=0.11$, not at $x=0.13$. In the vicinity of the singular composition, where charge ordering occurs,[32] it is possible to have a substantial fluctuation towards charge ordering. The application of a magnetic field may enhance such a fluctuation.

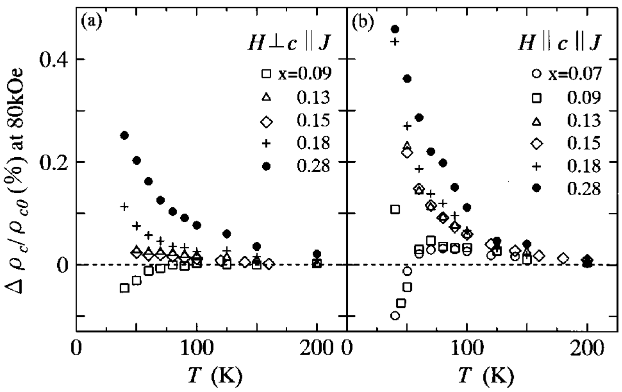

FIG. 14. Temperature dependence of transverse (a) and longitudinal (b) out-of-plane magnetoresistance in LSCO at 80 kOe.

The other possibility is related to the van Hove singularity. The van Hove singularity arises from a saddle point in the energy vs momentum relation. Theoretically, the resultant high density of states (DOS) at the Fermi level has been suggested to enhance T_c.[37] Experimentally, angle-resolved photoemission studies have found that the van Hove singularity is located right below the Fermi level in optimally doped YBCO (Ref. 38) and BSCCO.[39] Although direct observation by photoemission spectroscopy has not yet been achieved for LSCO, an ultrasonic measurement[40] suggests the existence of a narrow DOS peak, at a doping level slightly below the optimal composition $x = 0.15$, where we have observed the anomalous H-linear MR.

D. Out-of-plane magnetoresistance

Strong two dimensionality has been recognized as one of the most distinct properties of high-T_c cuprates. Doped holes appear to be strongly confined within the CuO_2 plane. Experimentally observed anisotropy in the resistivity[5] and the spectral weight obtained by optical measurements[41] are much greater than the one obtained from band structure calculations. The temperature dependence of the out-of-plane resistivity is semiconducting in the underdoped region down to T_c and therefore might diverge at $T = 0$ limit. This so-called "charge confinement" has been frequently discussed in terms of the non-Fermi-liquid nature of the ground state. As we have shown in the previous section, we also observed a quite unusual behavior in the out-of-plane MR. By plotting the temperature dependence of the MR at 80 kOe in Fig. 14, the evolution of the MR with doping can be clearly illustrated. Both longitudinal and transverse MR decrease monotonically, with decreased hole doping.

In the optimally doped to overdoped superconducting phases, the transverse out-of-plane MR is scaled by H/ρ_{a0} and the longitudinal one is scaled by H/T. Although we do not yet understand the origin of the appreciable longitudinal MR, we do not presume that this arises from an isotropic spin contribution, since the system is highly anisotropic. Assuming that the transverse MR simply consists of an orbital contribution, the scaling implies that the orbital MR behaves similarly to the in-plane MR, though the temperature dependence of the out-of-plane resistivity is distinctly different from that of the in-plane resistivity. This means that the in-plane scattering rate is somehow involved in the out-of-plane transport.

Kumar and Jayannavar[42] showed that, when the interlayer hopping rate is smaller than the in-plane scattering rate τ_a^{-1}, coherent transport becomes impossible. As a result, interlayer tunneling t_c is renormalized by the in-plane scattering rate, as $t_c^* \sim (t_c/\tau_a) t_c$. Their scenario may provide a possible explanation for the observed anomalous scaling of transverse MR. However, in order to explain the temperature dependence of ρ_c which is distinctly different from that of the in-plane resistivity, a coupling to bosonic degrees of freedom with the acoustic phonon has to be invoked.

In the underdoped region, a pronounced isotropic negative MR shows up at low temperatures. As seen from Fig. 2, this negative MR is observed when the temperature dependence of ρ_c is strongly semiconducting. In this sense, the negative MR appears to be directly related to the mechanism of charge confinement. Note that the in-plane resistivity is metallic in the corresponding temperature range. Therefore, carrier localization is highly unlikely as the mechanism to explain the negative MR in this case.

A similar negative MR has been observed in Bi and Y123 systems.[10,43,44] In the Bi2212 system, Yan *et al.* observed that the magnitude of the negative MR is thermally activated with an activation energy of 300 K. In the present LSCO system, since the negative contribution becomes visible at temperatures lower than in the Bi2212 system, the corresponding energy scale appears to be smaller than Bi2212. It has turned out that the negative MR in the present study does not show any activation-type temperature dependence.

Since the negative contribution appears to be almost isotropic, the origin of the negative MR should be ascribed to spin degrees of freedom. As pointed out by Yan *et al.*, an attractive scenario for the spin-derived negative MR may be that the interlayer charge transport is prevented by spin-singlet-pair formation associated with a spin gap. Therefore, the applied magnetic field reduces the out-of-plane resistivity by breaking up the spin-singlet pairs. The negative MR is observed only in the underdoped region where the pseudo spin gap has been generally observed. However, in LSCO, a pseudo spin gap has not been observed so far. Nevertheless, underdoped LSCO shows unusual behaviors[45] analogous to underdoped YBCO (Refs. 46–48) in terms of static susceptibility and the Hall effect, which appears to be closely related to the spin gap.

V. SUMMARY

We have performed systematic measurements of the in-plane and the out-of-plane magnetoresistance for $La_{2-x}Sr_xCuO_4$ single crystals over a composition range between $x = 0.07$ and 0.28. In the overdoped nonsuperconducting metal region, both in-plane and out-of-plane MR were well scaled by the conventional Kohler's rule, which is consistent with the finding that the system is an anisotropic 3D Fermi liquid in this composition range. In the superconducting phase, a superconducting fluctuation substantially contributes to the transverse in-plane MR. This brings about a difficulty in deducing normal-state properties, particularly in the underdoped region. We propose from the MR data for the underdoped region that the AL term is the only significant contribution to the fluctuation conductivity, and this is suggestive of anisotropic pairing. By subtracting the fluctuation conductivity consisting of the AL term alone, the normal-state MR has been estimated. The estimated normal-state MR apparently violates Kohler's rule, which supports the existence of two distinct scattering rates τ_{tr}^{-1} and τ_H^{-1}, for the optimally doped to overdoped superconducting phases.

Furthermore, two singular compositions were noticed in the in-plane MR for the underdoped samples. First, anomalously large H-linear MR is observed around $x=0.13$. Second, the influence of the 1/8 anomaly is clearly identified around $x=0.11$ as a suppression of the superconducting fluctuations.

The transverse out-of-plane MR in the optimally doped to overdoped superconducting regions is found to be scaled by (H/ρ_{a0}). This result suggests that the in-plane scattering process is somehow involved in interlayer transport. Also, the longitudinal out-of-plane MR in these regions is scaled by (H/T). In the underdoped region, a negative component in the out-of-plane MR, closely related to the diverging behavior of ρ_c with decreasing temperature, is observed at low temperatures. The isotropic magnitude of this component suggests that the spin degrees of freedom play a significant role in charge confinement within the CuO_2 plane.

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