Anisotropic Magnetoresistance in Lightly Doped $La_{2-x}Sr_xCuO_4$: Impact of Antiphase Domain Boundaries on the Electron Transport

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Detailed behavior of the magnetoresistance (MR) is studied in lightly doped antiferromagnetic $La_{1.99}Sr_{0.01}CuO_4$, where, thanks to the weak-ferromagnetic moment due to spin canting, the antiferromagnetic (AF) domain structure can be manipulated by the magnetic field. The MR behavior demonstrates that CuO_2 planes indeed contain antiphase AF-domain boundaries in which charges are confined, forming antiphase stripes. The data suggest that a high magnetic field turns the antiphase stripes into in-phase stripes, and the latter appear to give better conduction than the former, which challenges the notion that the antiphase character of stripes facilitates charge motion.

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In high-T_c cuprates, there is growing evidence that charges and spins self-organize in CuO_2 planes in a peculiar striped manner, where the doped holes are arranged in fluctuating lines, "charged stripes," that separate antiferromagnetic (AF) domains [1–3]. This intriguing microscopic state has been proposed to be responsible for many unusual properties of cuprates [4–9], but information on the role of stripes is still quite scarce.

Recently, it has been found that lightly doped $YBa_2Cu_3O_{6+x}$ (YBCO) and $La_{2-x}Sr_xCuO_4$ (LSCO) crystals develop a remarkable *in-plane* resistivity anisotropy upon decreasing temperature, which has been attributed to the self-organization of holes into unidirectional conducting stripes [8]. Moreover, in YBCO, an application of the magnetic field induces a persistent change in the in-plane anisotropy, presumably caused by some rearrangement of the stripes [9]. If this field-induced phenomenon is indeed related to the inherent striped structure of CuO_2 planes [10], similar features should be generic to cuprates, and by manipulating the stripes with a magnetic field one should be able to gain insights into their roles in macroscopic properties.

It is thus natural to turn to the LSCO system, where clear unidirectional striped structure has been observed by neutron scattering [11]. What makes LSCO even more attractive for the magnetoresistance study is a weak-ferromagnetic (FM) component that always accompanies the AF order: In LSCO, the spins in CuO_2 planes are slightly canted from the direction of the staggered magnetization, providing a weak FM moment whose direction is uniquely linked with the *phase* of the AF order [7,12,13]. As a result, once CuO_2 planes develop a pattern of AF domains that are separated by antiphase boundaries [2,7,11], the same pattern of FM moments emerges as well. Apparently, by using an external magnetic field one should be able to manipulate the domain structure in LSCO in quite the same way as in usual ferromagnets [14]; a large enough field should drive undoped or lightly doped LSCO into a weak-ferromagnetic state [12], where all the weak FM moments are aligned and the magnetic domain boundaries, if any, are completely wiped out. The consequent resistivity evolution would indicate how the AF-domain boundaries (stripes) are important for the electron transport.

Following this anticipation, we study the anisotropic magnetoresistance (MR) in lightly doped, antiferromagnetic $La_{1.99}Sr_{0.01}CuO_4$ single crystals, and find that a large magnetic field actually has a significant influence on the charge transport. The change in the in-plane and out-of-plane resistivity (ρ_{ab} and ρ_c) at 14 T is observed to be as large as a factor of 2 and 4, respectively, at low-temperature. In particular, the in-plane MR behavior demonstrates that in zero field each CuO_2 plane indeed contains antiphase domain boundaries, and that the high magnetic field unifies the phase of the AF ordering and wipes out the phase boundaries. We argue that the holes in the phase-unified state in high magnetic fields are still confined in stripes, which necessarily constitute in-phase domain boundaries. Thus, in lightly doped LSCO, the magnetic field has an intriguing function of switching the stripes from antiphase boundaries to in-phase ones.

The high-quality $La_{2-x}Sr_xCuO_4$ single crystals are grown by the traveling-solvent floating-zone technique and carefully annealed in pure helium to remove excess oxygen. Resistivity measurements are carried out by the ac four-probe method on samples that are cut and polished into suitable shapes. The particular samples reported here were made to be a thin strip $3000 \times 420 \times 70\ \mu m^3$ for ρ_{ab} and a narrow bar $115 \times 280 \times 2200\ \mu m^3$ for ρ_c. Upon measuring ρ_{ab}, special care is taken to avoid an admixture of ρ_c: upon thinning the sample, its face is adjusted to the ab crystal plane with an accuracy better than 1°, and the current contacts are carefully placed to cover the sample's side faces. Also, since we have recently found that the crystallographic twins in high-quality LSCO crystals can move under applied magnetic fields [15] and it is hard to control this effect, we cut the sample at 45° to the orthorhombic a and

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b axes (i.e., along the Cu-O-Cu direction) so that the ρ_a and ρ_b components are averaged. The MR is measured by sweeping the magnetic field at fixed temperatures stabilized by a capacitance sensor with an accuracy of $\sim$1 mK. The angular dependence of the MR is determined by rotating the sample within a 200° range under constant magnetic fields of $\pm$14 T. Magnetization measurements are performed on large ($\sim$ 0.5 g) detwinned single crystals [7].

Although doping 1% of holes into CuO_2 planes is not enough to suppress the AF order (T_N is still 230–240 K [5]), it nevertheless results in the appearance of a metal-like in-plane conduction at moderate temperatures (Fig. 1). However, the mechanism that facilitates the charge motion within CuO_2 planes is apparently irrelevant to the out-of-plane transport, causing the transport to be quasi-2D with the resistivity anisotropy ρ_c/ρ_{ab} of up to several thousands (inset of Fig. 1). Note that the 2D-conductivity features are essentially a finite-temperature property at this low doping, since the anisotropy sharply diminishes as $\rho_{ab}(T)$ loses its metal-like behavior at low temperatures (for $x = 0.01$, $\rho_c/\rho_{ab} \approx 100$ at $T = 13$ K).

The in-plane MR, $\Delta\rho_{ab}/\rho_{ab}$, measured in $La_{1.99}Sr_{0.01}CuO_4$ crystals for the magnetic field H applied parallel to CuO_2 planes [Fig. 2(a)] surprisingly resembles that of lightly doped YBCO [9]; namely, the MR is negative, follows a T-independent curve at low fields, and tends to saturate above some threshold field H_{th}. This similarity, being present despite a notable distinction between LSCO and YBCO in both the crystal and magnetic structures [7,12], demonstrates that the observed MR behavior is inherent in the lightly doped CuO_2 planes. Nevertheless, there are also several important differences between the MR features in LSCO and YBCO. First, in LSCO the saturation field as well as the MR values are scaled up so that $\Delta\rho_{ab}/\rho_{ab}$ at 14 T exceeds 1% already at high temperatures and reaches 30–40% at 10 K (in comparison with $\sim$1% in YBCO [9]); thus, the impact of the magnetic field is no more weak. Second, the angular dependences of the MR look quite different: While in YBCO $\Delta\rho_{ab}/\rho_{ab}$ changes its sign in a d-wave manner upon rotating the magnetic field within the ab plane [9], in LSCO it is always negative.

Detailed angular dependence study reveals that both the in-plane and out-of-plane MR of LSCO exhibit a clear twofold symmetry upon rotating the magnetic field within the ab plane (Figs. 3 and 4), which is particularly evident for the ρ_c crystal that is almost single domain according to x-ray data. The $\Delta\rho_c/\rho_c$ data for 130 K shown in Fig. 3 are surprisingly well described by a simple $A + B\sin^2\alpha$ dependence. Apparently, this simple $\sin^2\alpha$ dependence, combined with the perfect $\Delta\rho_c/\rho_c \propto H^2$ behavior observed at 130 K [Fig. 2(c)], indicate that *only the magnetic-field component along the orthorhombic b-axis, $H_b = H\sin\alpha$, is responsible for the angular-dependent part of the MR.* The MR follows the $\sin^2\alpha$ curve as long as the magnetic field stays below the saturation field H_{th}; at 210 K, H_{th} is reduced to 9–10 T [Fig. 2(b)], and the MR measured at $H = 14$ T shows a constant value over some range of angles (Fig. 3).

The behavior of $\Delta\rho_{ab}/\rho_{ab}$ in Fig. 4 looks different from that of $\Delta\rho_c/\rho_c$, partly because there are two types of orthogonal crystallographic domains (twins). Also, the H dependence of $\Delta\rho_{ab}/\rho_{ab}$ turns out to be $\propto H^n$ with $n > 2$ for $H < H_{th}$ [16], and this "anharmonicity" is responsible for the rather complicated angular dependence. However, by using the experimental data of $\Delta\rho_{ab}/\rho_{ab}(H)$ at $H \parallel b$ [Fig. 2(a)] and the ratio of crystallographic domains, we can well reproduce the observed angular dependence of the MR at both 130 and 210 K in Fig. 4, assuming that only the b component of magnetic field is responsible. Thus, in both ρ_{ab} and ρ_c the angular dependence of the MR is governed solely by the b component of H when the field is applied in-plane.

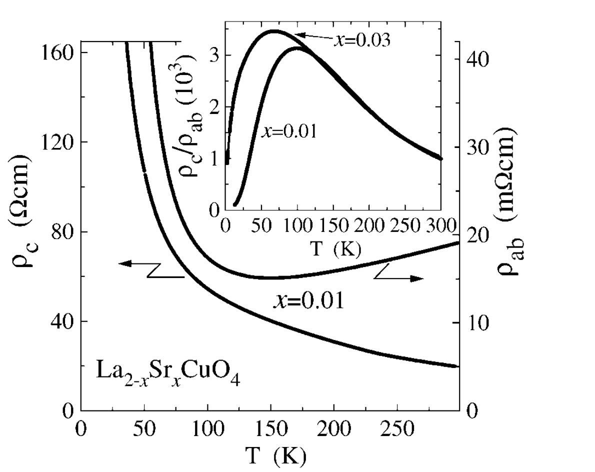

FIG. 1. $\rho_c(T)$ and $\rho_{ab}(T)$ of $La_{2-x}Sr_xCuO_4$ ($x = 0.01$) single crystals used for the MR measurements. Inset: Resistivity anisotropy ρ_c/ρ_{ab} for LSCO crystals with $x = 0.01$ and 0.03.

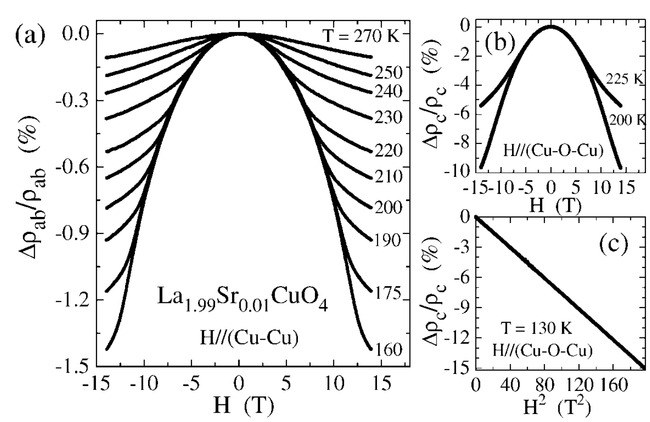

FIG. 2. (a) The MR in ρ_{ab} of $La_{1.99}Sr_{0.01}CuO_4$ for the in-plane magnetic field applied along the Cu-Cu (diagonal) direction, which is 45° to the current ($I \parallel$ Cu-O-Cu). (b) The MR in ρ_c for $H \parallel$ Cu-O-Cu at high temperatures. (c) $\Delta\rho_c/\rho_c$ at 130 K as a function of H^2.

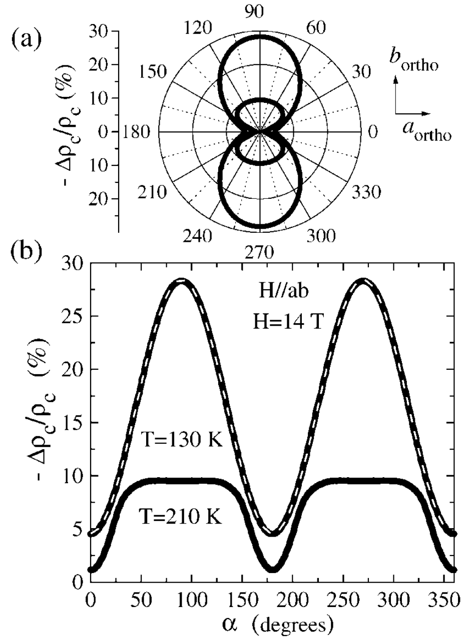

FIG. 3. Angular dependences of $\Delta\rho_c/\rho_c$ at $T = 130$ K and 210 K in (a) polar and (b) linear coordinates (arrows indicate the directions of the orthorhombic crystal axes). The white dashed line in (b) shows the fit with $\Delta\rho_c/\rho_c = A + B\sin^2\alpha$.

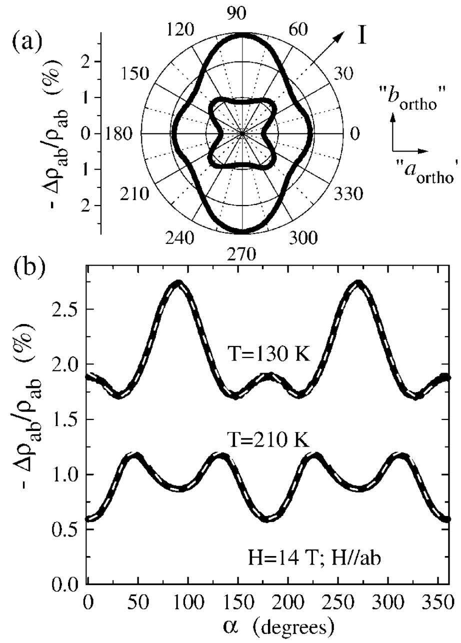

FIG. 4. Angular dependences of $\Delta\rho_{ab}/\rho_{ab}$ at $T = 130$ K and 210 K in (a) polar and (b) linear coordinates. The white dashed lines in (b) show the fits described in the text.

When the magnetic field is applied along the c axis, both the in-plane and out-of-plane MR exhibit a steplike decrease [Fig. 5(a)] similar to that reported by Thio *et al.* for $La_2CuO_{4+\delta}$ [12]. The salient point here is the magnitude of the MR: $|\Delta\rho_{ab}/\rho_{ab}|$ grows up to $\sim$50% at low temperatures [Fig. 5(b)] and $|\Delta\rho_c/\rho_c|$ reaches $\sim$75% [Fig. 5(c)], that is, the magnetic field is capable of reducing the resistivity by a factor of 2 and 4, respectively.

By now, the influence of magnetic fields on the AF spin order in undoped La_2CuO_4 has been fairly well understood [7,12]. At zero field, spins are aligned almost perfectly along the b axis, and just slightly canted towards the c axis, owing to the Dzyaloshinskii-Moriya (DM) interaction; the weak FM moments induced by this spin canting have opposite directions in adjacent CuO_2 planes so that no net moment is observed at zero field. When high enough magnetic fields are applied along the c axis, the weak FM moments in every second CuO_2 plane switch their orientation through a first-order transition [12,13], which is manifested in a steplike increase in the magnetization [Fig. 5(d)]. Since the direction of the canted moments is uniquely linked with the local *phase* of the AF order, this *phase* also switches in every second CuO_2 plane. On the other hand, when $H \parallel b$ is applied, the weak FM moments, which are confined to the bc plane due to the DM vector $\mathbf{D} \parallel a$ [7], smoothly rotate from the c to b direction to become parallel to the field. In any case, a magnetic field applied within the bc plane eventually aligns all the weak FM moments and unifies the phase of the AF order over the crystal; note that since weak FM moments are confined to the bc plane, the field $H \parallel a$ can hardly alter the spin order.

Apparently, the anisotropic magnetic-field effect on the spin order correlates well with what we see in the field and angular dependences of the MR. Therefore, it is natural to assert that the resistivity in LSCO is somehow affected by the pattern of the phase of the AF order; in fact, a large MR in $La_2CuO_{4+\delta}$ reported by Thio *et al.* [12,13] was attributed to an extraordinary sensitivity of the *out-of-plane* conductivity to the relative spin ordering in adjacent CuO_2 planes [13,17]—the behavior reminiscent of the intrinsic spin-valve effects in manganites [18]. What is important in the present data is, however, that the *in-plane* resistivity shows clear and large changes upon unifying the phase of the AF order. Given the quasi-2D conduction in our LSCO crystals ($\rho_c/\rho_{ab} \sim 10^3$), the *in-plane* transport can hardly be sensitive to relative phases of the AF order in adjacent CuO_2 planes, and therefore it must be the phase changes *within* the CuO_2 planes and the removal thereof that is responsible for the peculiar MR in ρ_{ab}. This means that the MR behavior in ρ_{ab} gives evidence that each CuO_2 plane intrinsically contains a set of antiphase boundaries in zero field.

Given that the antiphase boundaries exist in the CuO_2 planes, an important question is whether the holes are trapped in those boundaries. Although theoretical calculations show they do [19] (they even suggest that it is the charges that dictate the antiphase structure), it is desirable to draw a conclusion from experiments. In this regard, the temperature dependence of $\Delta\rho_{ab}/\rho_{ab}$ [Fig. 5(b)] is very useful: $|\Delta\rho_{ab}/\rho_{ab}|$ is quite small when the conduction is metal-like, but grows dramatically in the

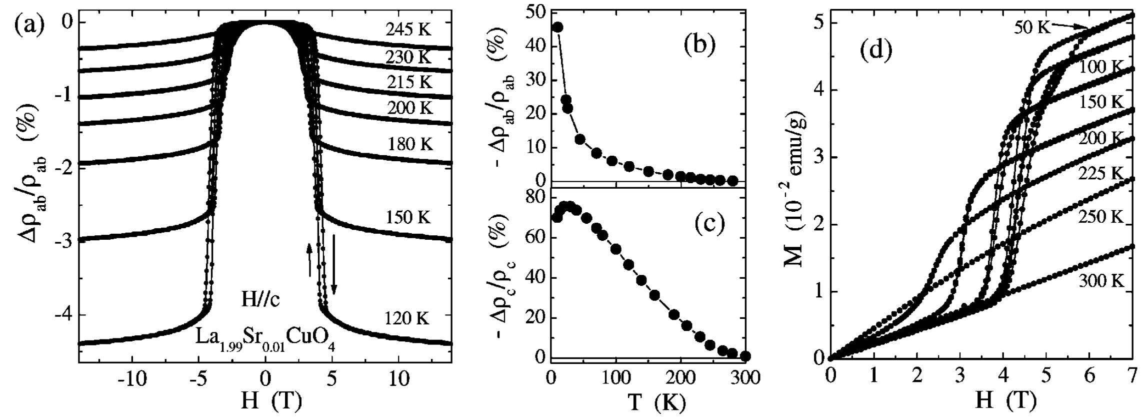

FIG. 5. (a) The MR in ρ_{ab} of $La_{1.99}Sr_{0.01}CuO_4$ for $H \parallel c$ at high temperatures; note the hysteresis marked by arrows. (b), (c) T dependences of the MR at 14 T for ρ_{ab} and ρ_c. (d) Magnetization for $H \parallel c$ illustrating the WF transition.

low-temperature insulating region. If the holes are uniformly distributed and the antiphase boundaries are working as *scatterers* of holes, the removal of these boundaries should primarily affect the scattering rate of holes; such a change should have more significant effect in the metal-like regime rather than in the insulating regime, where the conduction is governed not by the scattering but by hopping. If, on the other hand, the primary function of the boundaries is to confine holes, the effect of $H \parallel c$ is expected to be more drastically observed in the insulating regime, since the confinement potential changes. Clearly, our data indicate that the latter is the case, which means that in zero field the holes are confined in the antiphase boundaries, forming the charge stripes.

If one accepts the above conclusion, a puzzling aspect of our data is that the wiping out of the antiphase boundaries with magnetic fields results in a noticeable *decrease* in ρ_{ab}; this appears to contradict the usual notion that the antiphase stripes are formed to facilitate the hole motion in Mott insulators [1]. One possibility that resolves this puzzle is that the stripes do not "evaporate" in high magnetic fields but change into in-phase stripes. In fact, theoretical calculations show [19] that the domain-wall formation is favored over the uniform distribution of charges, and it appears [20] that the energetics to determine whether the domain walls (stripes) are in-phase or antiphase are rather subtle; thus, it is actually likely that the in-phase stripes are formed when the antiphase stripes are prohibited. To understand the better conduction through the in-phase stripes compared to the antiphase stripes is probably more challenging, but this might be resolved if one allows the hole filling in the stripes to be different in the two states [20], which naturally changes the conductivity through the stripes. While this last point is already highly speculative, our experimental data offer a good testing ground for theories of stripes in the cuprates.

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