Anisotropic Magnetoresistance in Lightly Doped La$_{2-x}$Sr$_x$CuO$_4$: Impact of Anti-Phase Domain Boundaries on the Electron Transport

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(Dated: October 31, 2018)

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 anti-phase AF domain boundaries in which charges are confined, forming anti-phase stripes. The data suggest that a high magnetic field turns the anti-phase stripes into in-phase stripes, and the latter appear to give better conduction than the former, which challenges the notion that the anti-phase character of stripes facilitates charge motion.

PACS numbers: 74.25.Fy, 74.20.Mn, 74.72.Dn

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. This intriguing microscopic state has been proposed to be responsible for many unusual properties of cuprates, but information on the role of stripes is still quite scarce. Recently, it has been found that lightly doped YBa$_2$Cu$_3$O$_{6+y}$ (YBCO) and La$_{2-x}$Sr$_x$CuO$_4$ (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. 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. If this field-induced phenomenon is indeed related to the inherent striped structure of CuO$_2$ planes, 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. 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. As a result, once CuO$_2$ planes develop a pattern of AF domains that are separated by anti-phase boundaries, 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: a large enough field should drive undoped or lightly-doped LSCO into a weak-ferromagnetic state, 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 ($\rho_{ab}$ and $\rho_c$) at 14 T is observed to be as large as a factor of two and four, respectively, at low temperature. In particular, the in-plane MR behavior demonstrates that in zero field each CuO$_2$ plane indeed contain anti-phase 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 anti-phase boundaries to in-phase ones.

The high-quality La$_{2-x}$Sr$_x$CuO$_4$ 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 $\rho_{ab}$ and a narrow bar 115 $\times$ 280 $\times$ 2200 $\mu$m$^3$ for $\rho_c$. Upon measuring $\rho_{ab}$, a special care is paid to avoid an admixture of $\rho_c$: 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 and it is hard to control this effect, we cut the sample at 45° to the orthorhombic $a$ and $b$ axes (i.e., along the Cu-O-Cu direction) so that the $\rho_c$ and $\rho_b$ components are averaged. The MR is measured by sweeping...
the magnetic field at fixed temperatures stabilized by a capacitance sensor with an accuracy of ~ 1 mK. The angular dependence of the MR is determined by rotating the sample within a 200° range under constant magnetic fields of ±14 T. Magnetization measurements are performed on large (~0.5 g) detwinned single crystals [2]. Although doping 1% of holes into CuO planes is not enough to suppress the AF order (TN is still 230-240 K [3]), it nevertheless results in appearance of a metal-like in-plane conduction at moderate temperatures (Fig. 1). However, the mechanism that facilitates the charge motion within CuO planes is apparently irrelevant to the out-of-plane transport, causing the transport to be quasi-2D with the resistivity anisotropy ρc/ρab 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 ρab(T) loses its metal-like behavior at low temperatures (for x = 0.01, ρc/ρab ≈ 100 at T = 13 K).

The in-plane MR, Δρab/ρab, measured in La1.99Sr0.01CuO4 crystals for the magnetic field H applied parallel to CuO2 planes [Fig. 2(a)] surprisingly resembles that of lightly doped YBCO [3]; namely, the MR is negative, follows a T-independent curve at low fields, and tends to saturate above some threshold field Hth. This similarity, being present despite a notable distinction between LSCO and YBCO in both the crystal and magnetic structures [4][12], demonstrates that the observed MR behavior is inherent in the lightly doped CuO2 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 Δρab/ρab at 14 T exceeds 1% already at high temperatures and reaches 30–40% at 10 K (in comparison with ~1% in YBCO [4]); thus, the impact of the magnetic field is no more weak. Second, the angular dependences of the MR look quite different: While in YBCO Δρab/ρab changes its sign in a d-wave manner upon rotating the magnetic field within the ab plane [4], 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 two-fold symmetry upon rotating the magnetic field within the ab plane (Figs. 3 and 4), which is particularly evident for the ρc-crystal that is almost single-domain according to x-ray data. The Δρc/ρc data for 130 K shown in Fig. 3 are surprisingly well described by a simple A + B sin²α dependence. Apparently, this simple sin²α dependence, combined with the perfect Δρc/ρc ∝ H² behavior observed at 130 K [Fig. 2(c)], indicate that only the magnetic field component along the orthorhombic b-axis, Hb = H sinα, is responsible for the angular-dependent part of the MR. The MR follows the sin²α curve as long as the magnetic field stays below the saturation field Hth; at 210 K, Hth 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 Δρab/ρab in Fig. 4 looks different from that of Δρc/ρc, partly because there are two types of orthogonal crystallographic domains (twins). Also, the H dependence of Δρab/ρab turns out to be ∝ Hn with n > 2 for H < Hth [10], and this “anharmonicity” is responsible for the rather complicated angular dependence. However, by using the experimental data of Δρab/ρab(H) at H || b [Fig. 2(a)] and the ratio of crystallographic domains, we can well reproduce the observed angular dependence of the MR at both 130 K and 210 K in Fig. 4, assuming that only the b-component of magnetic field is responsible. Thus, in both ρab and ρc, the angular dependence of the MR is governed solely by the b-component of H when the field is applied in-plane.

When the magnetic field is applied along the c-axis, both the in-plane and out-of-plane MR exhibit a step-like decrease [Fig. 5(a)] similar to that reported by Thio.
By now, the influence of magnetic fields on the AF spin order in undoped La$_2$CuO$_4$ has been fairly well understood \cite{12,13}. 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 cantiing 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 \cite{12,13}, which is manifested in a step-like 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 $D \parallel a$ \cite{12,13}, 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$_2$CuO$_4$+δ reported by Thio et al. \cite{12,13} was attributed to an extraordinary sensitivity of the out-of-plane conductivity to the relative spin ordering in adjacent CuO$_2$ planes \cite{13,17} – the behavior reminiscent of the intrinsic spin-valve effects in manganites \cite{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 ($\rho_{r}/\rho_{ab} \sim 10^{3}$), 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 $\rho_{ab}$. This means that the MR behavior in $\rho_{ab}$ gives evidence that each CuO$_2$ plane intrinsically contains a set of anti-phase boundaries in zero field.

Given that the anti-phase 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 \cite{10} (they even suggest that it is the charges that dictate the anti-phase 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 low-temperature insulating region. If the holes are uniformly distributed and the anti-phase boundaries

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**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.
FIG. 5: (a) The MR in \( \rho_{ab} \) 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 \( \rho_{ab} \) and \( \rho_c \). (d) Magnetization for \( H \parallel c \) illustrating the WF transition.

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 anti-phase boundaries, forming the charge stripes.

If one accepts the above conclusion, a puzzling aspect of our data is that the wiping out of the anti-phase boundaries with magnetic fields results in a noticeable decrease in \( \rho_{ab} \); this appears to contradict the usual notion that the anti-phase stripes are formed to facilitate the hole motion in Mott insulators. 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 that the domain-wall formation is favored over the uniform distribution of charges, and it appears that the energetics to determine whether the domain walls (stripes) are in-phase or anti-phase are rather subtle; thus, it is actually likely that the in-phase stripes are formed when the anti-phase stripes are prohibited. To understand the better conduction through the in-phase stripes compared to the anti-phase 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, 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.

We thank K. Segawa for invaluable technical assistance, and S. A. Kivelson and I. Tsukada for fruitful discussions.

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