Electrical Resistivity Anisotropy from Self-Organized One Dimensionality in High-Temperature Superconductors

Yoichi Ando, Kouji Segawa, Seiki Komiya, and A. N. Lavrov
Central Research Institute of Electric Power Industry, Komae, Tokyo 201-8511, Japan
(Received 31 July 2001; published 19 March 2002)

We investigate the manifestation of stripes in the in-plane resistivity anisotropy in untwinned single crystals of $La_{2-x}Sr_xCuO_4$ ($x = 0.02-0.04$) and $YBa_2Cu_3O_y$ ($y = 6.35-7.0$). It is found that both systems show strongly temperature-dependent in-plane anisotropy in the lightly hole-doped region and that the anisotropy in $YBa_2Cu_3O_y$ *grows* with decreasing y below $\sim$6.60 despite the decreasing orthorhombicity, which gives most direct evidence that electrons self-organize into a macroscopically anisotropic state. The transport is found to be easier along the direction of the spin stripes already reported, demonstrating that the stripes are intrinsically conducting in cuprates.

DOI: 10.1103/PhysRevLett.88.137005 PACS numbers: 74.25.Fy, 74.25.Dw, 74.20.Mn, 74.72.Bk

The mechanism of the high-temperature superconductivity is still not settled 15 years after its discovery, mostly because it is unclear how best to describe the strongly correlated electrons in the high-T_c cuprates. It has recently been discussed [1–14] that the electrons in cuprates self-organize into quasi-one-dimensional stripes, which might bring a paradigm shift in our way of understanding the two-dimensional (2D) electronic system in the cuprates. Though the self-organization is interesting in itself, the conventional wisdom suggests that the stripes are destructive to the superconductivity, because charge ordering would normally lead to an insulating state. However, there are intriguing theoretical proposals [10–12] that stripes can instead be responsible for the *occurrence* of the high-temperature superconductivity if they are conducting and meandering—properties that have never been clearly demonstrated before.

In this Letter, we report novel in-plane transport anisotropy in the cuprates, which gives direct evidence for the conducting charge stripes in these materials; the temperature dependence and the magnitude of the anisotropy strongly suggest the stripes to be meandering and forming an electronic liquid crystal [11]. The evidence is shown for two representative materials of the high-temperature superconductors, $La_{2-x}Sr_xCuO_4$ (LSCO) and $YBa_2Cu_3O_y$ (YBCO), highlighting the universality of the charge-stripe phenomenon in the cuprates. Most notably, the data for YBCO indicate that the charge stripes govern the transport in samples with T_c of as high as 50 K, demonstrating that theories of high-temperature superconductivity should inevitably consider the self-organization of the electrons as an integral part.

It is fair to say that the majority of the researchers today believe that the stripes are irrelevant to the superconductivity. This general belief comes not only from the conventional wisdom mentioned above but also from the current experimental situation, which can be summarized as follows: (i) strong evidence for the charge-stripe order has been reported [1] only for Nd-doped LSCO, where the superconductivity is strongly suppressed; (ii) in other superconducting cuprates, evidence [2–7] is reasonably strong for *spin* stripes, but not at all conclusive for *charge* stripes. Therefore, to really establish the charge stripe as a new paradigm, it is necessary to clarify whether *charges* truly self-organize into stripes in superconducting cuprates other than Nd-doped LSCO. Moreover, since the stripe order in cuprates may be just a more or less standard charge density wave or spin density wave, it is important to clarify whether the charge stripes in cuprates, if they exist, are intrinsically conducting; in fact, none of the previous works [1–9] directly show the relation between the stripe order and metallic conduction.

It is instructive to note that there is now little doubt about the existence of conducting charge stripes in the 2D electron gas in high Landau levels [15], for which a clear transport anisotropy [16,17] has been considered to be convincing evidence. If one could observe a similar resistivity anisotropy in the nearly square CuO_2 planes in the cuprates, that would most convincingly establish the existence of the conducting charge stripes. Recent neutron scattering experiments [4] have found static spin stripes that are unidirectional and extend along the a axis of the orthorhombic crystalline lattice in LSCO with $x \leq 0.05$ at low temperatures, which motivates us to search for the resistivity anisotropy in the lightly doped LSCO. It has also been suggested [3] that the stripes are unidirectional and run along the b axis in YBCO, which is the other system studied here; however, existence of the CuO chains [18], which also run along the b axis and are possibly conducting, may well contribute to the in-plane resistivity anisotropy in YBCO and thus a careful doping-dependence study is necessary to distinguish the stripe conductivity in the CuO_2 planes from the chain conductivity. Since these weakly orthorhombic cuprates (orthorhombicity is only up to 1.7%) [4,18] naturally develop twin structures in single crystals, it is necessary to detwin the crystals to make an in-plane anisotropy measurement.

The LSCO crystals with $x = 0.02-0.04$ used for this study are grown by the traveling-solvent floating-zone method [19]. After determining the crystallographic axes

 0031-9007/02/88(13)/137005(4)$20.00

using the x-ray Laue analysis, the LSCO crystals are cut into a platelet shape and are detwinned [20] under a uniaxial pressure. Although it is difficult to observe the twin structure in the *ab* face for LSCO, we found that the twins cause a clear washboardlike structure on the polished ac/bc face, which is observable with both an optical microscope and a scanning electron microscope (Fig. 1) [21]. Discovery of this feature enabled us to select only those LSCO crystals that are almost perfectly detwinned for the present measurement, while well-detwinned LSCO crystals were never available before. The YBCO crystals with $y = 6.35-7.0$ are prepared and characterized as is described elsewhere [22]. With YBCO crystals, we can easily select perfectly detwinned crystals by looking at the *ab* face with a polarized-light optical microscope.

The resistivity along the a axis (ρ_a) and the b axis (ρ_b) is measured by a straightforward four-terminal method with the accuracy and reproducibility of better than 10% [19,22]. For LSCO, it turned out that 10% accuracy was not good enough to determine the *ab* anisotropy; to obtain the most reliable data on the anisotropy of LSCO, we detwin the *same* piece of crystal *three times* from different directions; namely, the crystals are initially detwinned to be a-axis oriented along the current direction to measure ρ_a, then to be b-axis oriented to measure ρ_b without changing the contacts (thus the difference comes purely from the change in the axis orientation), and last to be a-axis oriented again to confirm that the first ρ_a data are recovered. Figures 2(a)–2(c) show the temperature dependences of ρ_a and ρ_b obtained this way for $x = 0.02$, 0.03, and 0.04, and Fig. 2(d) shows the resulting in-plane anisotropy ρ_b/ρ_a [23]. At high temperatures ρ_b/ρ_a is nearly 1, which is consistent with the weak orthorhombicity (only 1.5%) [4]; however, what is unusual is that ρ_b/ρ_a grows rapidly with decreasing temperature below ~150 K. It is useful to note that at room temperature ρ_b is slightly smaller than ρ_a for all x values and the anisotropy switches at lower temperature. Both the rapid growth and the switching of the anisotropy cannot be explained if one assumes that the anisotropy is due simply to the orthorhombicity of the crystal. If it is not due to the orthorhombicity, we must conclude that a self-organization of the electrons is responsible for the observed anisotropy behavior, because there is no other external source to cause the anisotropy in LSCO [24]. Since the preferred direction of the stripes is the a axis [4], the observed in-plane anisotropy ($\rho_a < \rho_b$) below ~100 K [25] indicates that the stripes are intrinsically conducting at finite temperature; this conclusion does not contradict the localization behavior at low temperatures, because charges in low-dimensional systems easily localize in the presence of disorder.

For YBCO, ρ_a and ρ_b are measured on different crystals, but they are respectively measured on at least three crystals for each composition and the data are confirmed to be very reproducible within 5%, as is demonstrated elsewhere [22]. Representative data sets of $\rho_a(T)$ and $\rho_b(T)$ for four values of y, including the upper ($y = 7.0$) and lower ($y = 6.35$) extremes of this study, are shown in Figs. 3(a)–3(d), and the anisotropy ratio, ρ_a/ρ_b, is shown in Fig. 4(a) for selected y. Previously, the in-plane resistivity anisotropy of YBCO has been reported [26] only for $y > 6.6$, where ρ_a/ρ_b monotonically decreases with decreasing y; this is consistent with the idea [26] that the anisotropy near optimum doping is caused (at least partly) by an additional conductivity of the CuO chains which are progressively destroyed [18] with decreasing oxygen content. However, when we extend the region of y to lower values, the result is surprising; as can be seen in Fig. 4(a), ρ_a/ρ_b at low temperatures turns out to grow with decreasing y for $y < 6.6$, and the temperature dependence

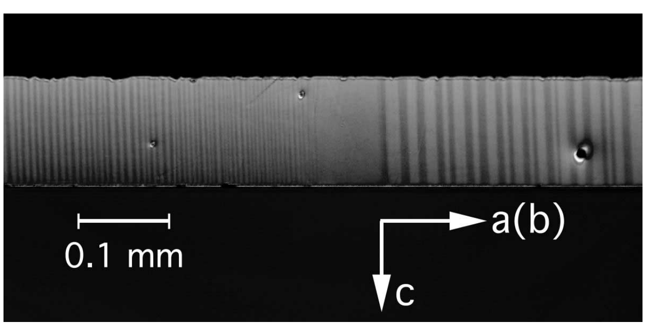

FIG. 1. Twin pattern on the ac/bc face of an as-grown LSCO crystal observed with an optical microscope. The contrast is caused by a washboardlike modulation on the surface [21], which is confirmed by a scanning electron microscope.

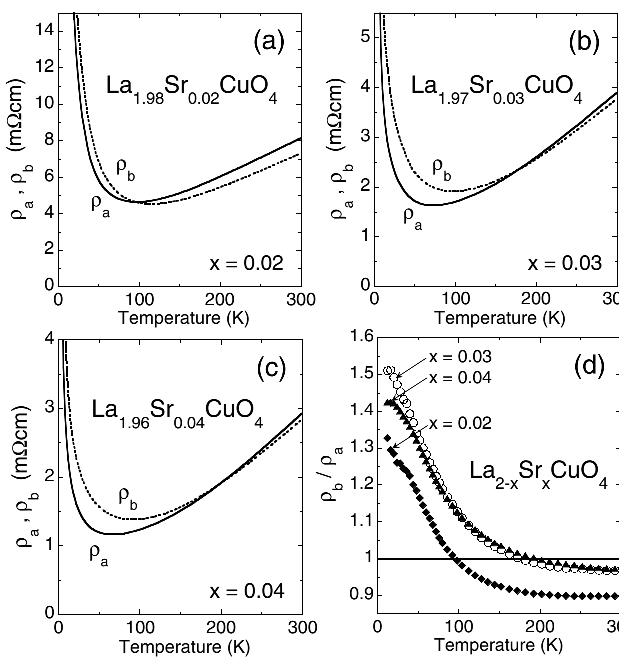

FIG. 2. Anisotropic resistivity (a)–(c) and the anisotropy ratio (d) of lightly doped LSCO. T dependences of ρ_a and ρ_b are shown for $x = 0.02$ (a), 0.03 (b), and 0.04 (c). Note that the spin stripes have been found [4] to run along the a axis, along which the resistivity becomes smaller at low temperatures.

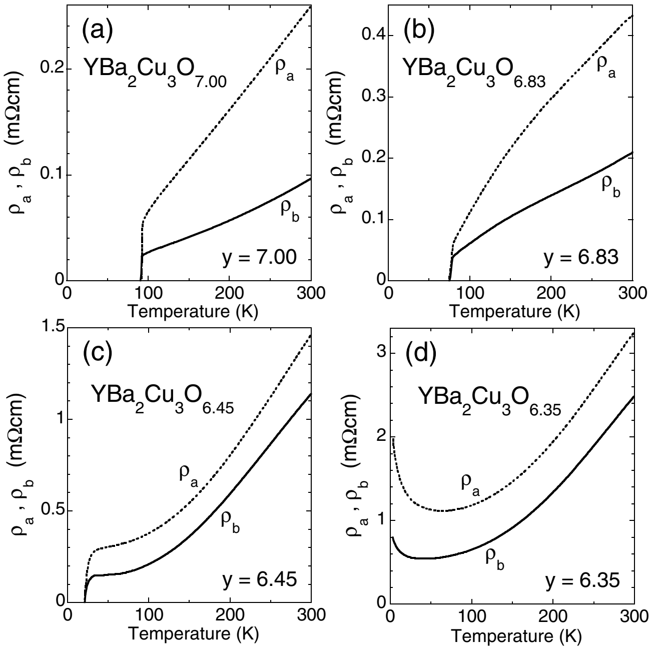

FIG. 3. Representative data sets of $\rho_a(T)$ and $\rho_b(T)$ for YBCO at selected y. The y values shown are 7.00 (a), 6.83 (b), 6.45 (c), and 6.35 (d). In nonsuperconducting samples at $y = 6.35$ (d), the anisotropy does not disappear even though the CuO chains are destroyed.

of ρ_a/ρ_b becomes similar to that of ρ_b/ρ_a for LSCO in the lightly doped region. Since Fig. 4(a) is rather complicated, the evolution of ρ_a/ρ_b in the y vs T plane is transparently depicted in Fig. 4(b) with a color map. One can see in Fig. 4(b) that with decreasing y down to ~6.6 the anisotropy gradually weakens, which is likely to reflect the diminishing contribution from the chains; however, the anisotropy starts to grow below $y \simeq 6.6$ at low temperatures, causing a novel peak at the lower left corner where ρ_a/ρ_b amounts to 2.5.

Because the orthorhombicity is gradually diminished [18] as the CuO chains are destroyed with decreasing y, the observed growth of ρ_a/ρ_b for $y < 6.6$ cannot be simply due to the orthorhombicity nor the chain conductivity; therefore, we are forced to admit that the growth of ρ_a/ρ_b with decreasing y is caused by a self-organization of the two-dimensional electrons in the CuO_2 planes into an anisotropic system, which becomes stronger as the carrier concentration is reduced. Note that a clear in-plane resistivity anisotropy is observed even in a nonsuperconducting YBCO at $y = 6.35$, where the orthorhombicity is about to disappear [18] (the measured lattice constants are $a = 3.871$ Å and $b = 3.861$ Å, giving only 0.26% orthorhombicity). Most likely, the remaining short fragments of the chains (that are aligned to the b axis upon detwinning) set a nonisotropic environment in which the electrons in the CuO_2 planes find the preferred orientation for their self-organization.

We note that there is strong evidence that the CuO chains in YBCO are metallic at $y \simeq 7.0$ [27,28] and thus they certainly contribute to the anisotropy in fully oxygenated samples; however, the chain conductivity is expected to be quickly suppressed with decreasing y because of the extreme sensitivity of one-dimensional (1D) systems to defects (even at $y = 6.90$, each chain contains 10% of defects and would normally be insulating). Therefore, it is possible that already near optimum doping the conductivity anisotropy is partly due to the (chain-induced) anisotropy in CuO_2 planes, which is actually suggested by a recent microwave measurement [28]. In heavily underdoped YBCO, the chain fragments are usually no longer than ten unit cells even when an ordered "ortho-II" phase is formed [29]; thus, the ortho-II phase is not expected to cause any noticeable conductivity contribution through the chains. In fact, the region of y where the ortho-II phase is most stable (6.5–6.6) shows the *smallest* in-plane anisotropy.

It should be remarked that the anisotropy ratio reaches only 2.5 in the self-organized phase, which seems too small for a "quasi-1D" stripe phase; in the ordinary quasi-1D systems, such as Bechgaard salts, the conductivity along the

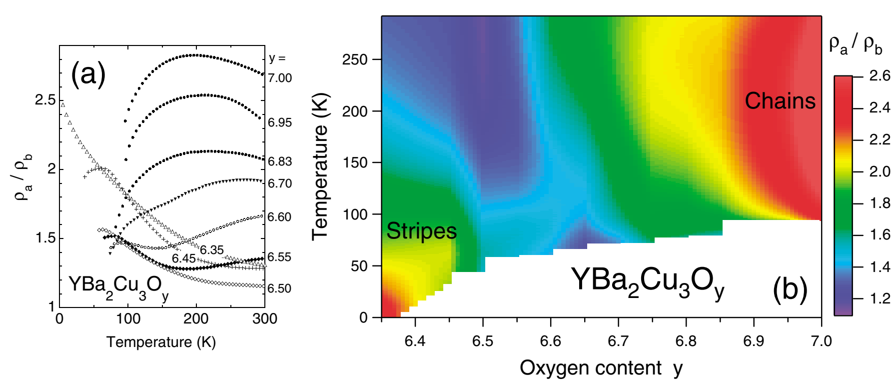

FIG. 4 (color). (a) Temperature dependences of ρ_a/ρ_b for selected y. (b) Evolution of ρ_a/ρ_b in the y vs T plane. The white region corresponds to the superconducting state. The CuO chains cause a peak at $y = 7.0$, which is gradually diminished as the chains are destroyed with decreasing y; on the other hand, a growth of ρ_a/ρ_b with further decreasing y, observable for $y < 6.60$, signals the self-organization of the electrons into charge stripes. The anisotropy ratio at $y = 6.35$, 6.45, 6.50, 6.55, 6.60, 6.65, 6.70, 6.75, 6.80, 6.83, 6.95, and 7.00 are the actual data, and linear interpolations are employed to generate the color map.

1D chains is usually a factor of 100 larger than that along the next best conducting direction. Thus, the simplistic picture of the rigid 1D stripes carrying current in the cuprates is clearly not valid. On the other hand, the much smaller anisotropy and its strong temperature dependence observed here are actually consistent with the behavior [15] of an electronic liquid crystal [11], where transverse fluctuations (quantum meandering) of the stripes are significant; it is useful to note that another self-organized stripe system, 2D electrons in high Landau levels, also shows [17] a rather small anisotropy ratio of up to 7 with a strong temperature dependence [30]. It is intriguing that the electronic liquid crystals are predicted [11] to be either a high-temperature superconductor or a two-dimensional anisotropic metal. The stripe phase of the lightly doped cuprates seems to be consistent with the latter, and the YBCO data for $y < 6.6$ strongly suggest that the superconductivity with T_c of at least 50 K is occurring in an electronic liquid crystal. If the charge transport at higher doping is also governed by the fluctuating stripes (as is suggested by the nearly doping-independent hole mobility [19]), it may actually be the case that the whole phenomenon of high-temperature superconductivity is realized as a ground state of an electronic liquid crystal.

In summary, we have found that the in-plane resistivity anisotropy in untwinned single crystals of LSCO and YBCO gives evidence for conducting charge stripes in these systems. The temperature dependence and the rather small magnitude of the anisotropy bear strong similarities to the nematic [15] charge stripes in the 2D electron gas in high Landau levels, suggesting that the electronic liquid crystals are likely to be realized in the cuprates. Moreover, the signature of an electronic liquid crystal is observed in YBCO with T_c of up to 50 K, which demonstrates that the electron self-organization is not a minor phenomenon in some extreme of the phase diagram but is rather an integral part of the physics in the cuprates.

We thank S. A. Kivelson for fruitful discussions and valuable comments.

[1] J. M. Tranquada, B. J. Sternlieb, J. D. Axe, Y. Nakamura, and S. Uchida, Nature (London) **375**, 561 (1995).

[2] K. Yamada *et al.,* Phys. Rev. B **57**, 6165 (1998).

[3] H. A. Mook, P. Dai, F. Dogan, and R. D. Hunt, Nature (London) **404**, 729 (2000).

[4] M. Matsuda *et al.,* Phys. Rev. B **62**, 9148 (2000), and references therein.

[5] A. W. Hunt, P. M. Singer, K. R. Thurber, and T. Imai, Phys. Rev. Lett. **82**, 4300 (1999).

[6] H. A. Mook and F. Dogan, Nature (London) **401**, 145 (1999).

[7] Y. Ando, A. N. Lavrov, and K. Segawa, Phys. Rev. Lett. **83**, 2813 (1999).

[8] T. Noda, H. Eisaki, and S. Uchida, Science **286**, 265 (1999).

[9] X. J. Zhou *et al.,* Science **286**, 268 (1999).

[10] V. J. Emery, S. A. Kivelson, and O. Zachar, Phys. Rev. B **56**, 6120 (1997).

[11] S. A. Kivelson, E. Fradkin, and V. J. Emery, Nature (London) **393**, 550 (1998).

[12] E. W. Carlson, D. Orgad, S. A. Kivelson, and V. J. Emery, Phys. Rev. B **62**, 3422 (2000).

[13] J. Zaanen, Science **286**, 251 (1999).

[14] A. L. Chernyshev, A. H. Castro Neto, and A. R. Bishop, Phys. Rev. Lett. **84**, 4922 (2000).

[15] E. Fradkin, S. A. Kivelson, E. Manousakis, and K. Nho, Phys. Rev. Lett. **84**, 1982 (2000).

[16] M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **82**, 394 (1999).

[17] M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **83**, 824 (1999).

[18] J. D. Jorgensen *et al.,* Phys. Rev. B **41**, 1863 (1990).

[19] Y. Ando, A. N. Lavrov, S. Komiya, K. Segawa, and X. F. Sun, Phys. Rev. Lett. **87**, 017001 (2001).

[20] A. N. Lavrov, Y. Ando, S. Komiya, and I. Tsukada, Phys. Rev. Lett. **87**, 017007 (2001).

[21] Across the twin boundary, the neighboring domains are orthorhombically distorted in opposite ways, and the polished surface appears to follow the direction of the crystallographic axis in each domain; this causes a washboardlike surface modulation.

[22] K. Segawa and Y. Ando, Phys. Rev. Lett. **86**, 4907 (2001).

[23] Since we could not confirm the perfection of the second detwinning with the contacts on the sample, these ρ_b/ρ_a data might slightly underestimate the true anisotropy; however, the ρ_b data shown here agree with the data obtained separately on ρ_b-measurement-dedicated samples.

[24] It is worth noting that in Figs. 2(a)–2(c) the positions of the minimum in the resistivity curves, which marks the onset of charge localization [19], are different between the a and b directions for all x values; such a behavior is not expected in an ordinary anisotropic metal, where the carriers in each band have an anisotropic effective mass with a single scattering rate.

[25] Though the spin stripes are observed only below ~70 K by neutrons [4], the magnetic susceptibility χ develops anisotropy from a much higher temperature [20], as does the resistivity. However, the Dzyaloshinskii-Moriya interaction makes the anisotropy in $\chi(T)$ complicated, negating a direct comparison to the anisotropy in $\rho(T)$.

[26] K. Takenaka, K. Mizuhashi, H. Takagi, and S. Uchida, Phys. Rev. B **50**, 6534 (1994).

[27] N. E. Hussey *et al.,* Phys. Rev. B **61**, R6475 (2000).

[28] R. Harris *et al.,* Phys. Rev. B **64**, 064509 (2001).

[29] H. Haugerud, G. Uimin, and W. Selke, Physica (Amsterdam) **275C**, 93 (1997), and references therein.

[30] The anisotropy ratio for this system was initially reported to be of order of 100 [16], which later turned out to be due to a geometric effect [17].