PHYSICAL REVIEW B **79**, 012501 (2009)

Fourfold symmetry in the anisotropy of the magnetoresistance of stripe-ordered $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ single crystals

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(Received 24 November 2008; published 12 January 2009)

A fourfold symmetry of the out-of-plane magnetoresistance (MR) of $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ [(LNSCO) $x=0.10$, 0.12, 0.15, and 0.18] single crystals was observed below the superconducting transition temperature T_c^{onset} by rotating magnetic field direction in the *ab*-plane of the crystals. This large anisotropy in MR of LNSCO compared with that of $La_{2-x}Sr_xCuO_4$ is mainly attributed to the static stripe-phase-induced vortex pinning. A similar fourfold symmetry in ac magnetization supports the pinning mechanism in the stripe phase. A further investigation indicates that the anisotropic MR depends on both the stripe-phase-induced vortex pinning and the superconductivity of the LNSCO system.

DOI: 10.1103/PhysRevB.79.012501 PACS number(s): 74.25.Fy, 74.25.Qt, 74.72.Dn

The stripe phase in high-T_c cuprates is one of the most important issues for understanding the mechanism of high-T_c superconductivity. Transport and neutron-scattering studies on $La_{2-x}Sr_xCuO_4$ (LSCO) and $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals support the stripe picture that the doped carriers aggregate into stripes and move in these "charge rivers" without disturbing the underlying antiferromagnetic CuO_2 planes.[1–3] In $La_{2-x}Ba_xCuO_4$ (LBCO) or $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (LNSCO) system, the static stripe phase appears after the structural transformation from the low-temperature orthorhombic (LTO) phase to the low-temperature tetragonal (LTT) phase.[4] It is found that the formation of static charge-stripe order raises an inhomogeneous superconducting state and induces unusual charge transport behaviors.[5,6]

As we know, the vortex state in a system with intrinsically modulated superconductivity is possibly different from that of a homogenous superconducting system. Therefore, it is of interest to study the vortex dynamics in the stripe-ordered state. It was found theoretically that the vortex for magnetic field perpendicular to CuO_2 plane is trapped in the weak superconducting structure outside of the charge stripe, as reported by Ichioka *et al.*[7] This scenario is similar to the "cross lattice" vortex state observed in $Bi_2Sr_2CaCu_2O_8$ under independently applied in-plane field and *c*-axis field.[8,9] In the "cross lattice" state, a pancake vortex is located on the Josephson vortex line as a result of the pinning by inhomogeneous superconducting state raised by the penetration of Josephson vortex. Although this stripe-phase pinning effect was proposed by studying the magnetization of $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ single crystals for field parallel to *c* axis,[10] it is still unclear how the static stripe phase interacts with the vortex matter, especially for the case of the field parallel to the CuO_2 plane. In this case, one can get the most intrinsic information for the interaction between the vortices and stripes that lie on the CuO_2 planes, which is very important for understanding the vortex dynamics in high-T_c superconductors. To further clarify this problem, the *c*-axis resistivity and the in-plane magnetization for magnetic fields parallel to the CuO_2 plane of LNSCO single crystals were studied. A fourfold symmetry is found in the *c*-axis magnetoresistance (MR) as well as the ac magnetization upon rotating the magnetic field within the *ab* plane, which suggests a stripe-phase-induced anisotropic flux pinning.

The single crystals of $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ with nominal Sr compositions of $x=0.10$, 0.12, 0.15, and 0.18 were grown by using a traveling solvent floating-zone furnace (model: FZ-T-4000-H, Crystal System Corp.) with a quartet ellipsoidal mirror heated by four halogen lamps. The growth method was similar to the previous reports.[11,12] The typical grown rods were 6 mm in diameter and 80 mm in length. The dimension of the samples used in the present transport measurements is $3\times1\times0.7$ mm^3 with long edge along the *c* axis. The angular error from the desired crystal axis was less than ±1°. Before measurements, the samples were annealed in air at 800 °C for 48 h to attain a proper oxygen content and achieve homogeneity. The *c*-axis resistance was measured by a four-probe technique using a Quantum Design Physical Property Measurement System (PPMS)-9. The ac magnetization was studied using a superconducting quantum interference device [(SQUID) Quantum Design, Magnetic Property Measurement System (MPMS)-XL]. The sample used for the magnetization measurement is shaped to a column with diameter of 2 mm and thickness of 1 mm along *c* axis. Magnetic fields were applied parallel to the *ab* plane of the crystals in all measurements.

It is known that the static stripes are along the Cu-Cu direction for a nonsuperconducting LSCO ($x<0.05$); while for the LTT phase of LNSCO, the static stripes are along the Cu-O-Cu direction and the stripes in adjacent CuO_2 planes are rotated by 90°.[13–15] Suppose the stripe may affect the vortex movement, it is very likely that the MR under in-plane fields along Cu-O-Cu and Cu-Cu directions would be different. Figure 1 displays the temperature dependencies of the out-of-plane resistivity ρ_c under different magnetic fields along Cu-O-Cu [$\theta=0°$, here θ is the angle between the direction of field and *a* (or *b*) axis of LNSCO] and Cu-Cu ($\theta=45°$) directions for the LNSCO crystals with $x=0.10$, 0.12, 0.15, and 0.18. For magnetic fields along the Cu-Cu direction, the broadening of the superconducting transition curves is slightly larger than that of the fields along Cu-O-Cu direc-

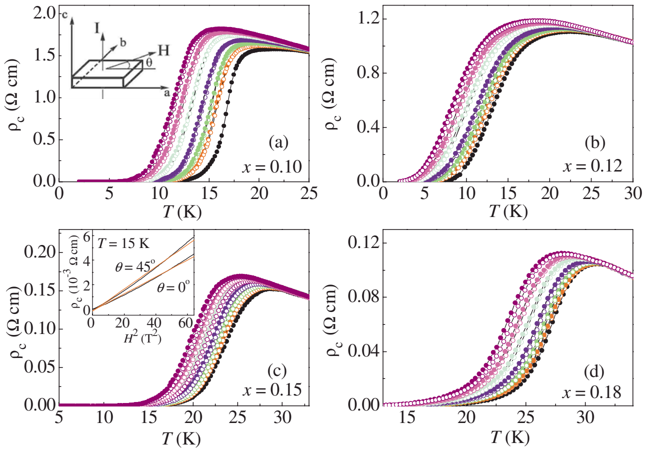

FIG. 1. (Color online) Temperature dependencies of ρ_c of $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (x=0.10, 0.12, 0.15, and 0.18) single crystals under magnetic fields of 0, 0.5, 1, 2, 4, 6, and 8 T, for θ=0° (blank dot) and θ=45° (solid dot). The inset in (c) is the variation of ρ_c as a function of H^2 at 15 K for LNSCO with x=0.15.

tion. To give a clear evidence for the difference, the magnetic field-dependent resistivities for θ=0° and θ=45° under a fixed temperature are plotted, as shown in Fig. 1(c) for LNSCO x=0.15 at 15 K. The field-dependent resistivity for θ =45° is obviously larger than that for θ=0°. These results strongly indicate the existence of the anisotropic in-plane field effect on the out-of-plane resistivity of LNSCO crystals.

In order to get a detailed image of the anisotropic in-plane field effect, the angular dependence of the out-of-plane MR $\{\Delta\rho_c/\rho_{c0}=[\rho_c(H)-\rho_c(0)]/\rho_c(0)\}$ was measured by rotating the sample within 200° range under the in-plane magnetic field. Figure 2 shows the angular dependences of MR for x=0.15 sample (T_c^{onset} of 31 K) at 15, 25, 30, and 40 K under a magnetic field of 1 T. The angular dependence of c-axis MR of LNSCO exhibits a fourfold symmetry upon rotating the magnetic field within the ab plane of the crystals below the resistive transition temperature T_c^{onset}, while such a symmetry disappears at 40 K which is above T_c^{onset}. It was found that the MR reaches a maximum and/or a minimum for the field along the Cu-Cu and/or the Cu-O-Cu directions, respectively.

Several origins may be responsible for the fourfold symmetry. The first possible origin is the d-wave symmetry of the superconducting gap, as reported in LSCO by Hanaguri *et al.*[16] and 60 K YBCO by Naito *et al.*[17] For comparison, the angular dependence of MR of LSCO x=0.15 single crystal which has a T_c^{onset} of 41 K was also studied. In our case, the fourfold symmetry in LNSCO is much larger than that in LSCO, as shown in Fig. 3, which is difficult to be explained by a simple d-wave symmetry of superconductivity. This fact indicates that the origin for the large anisotropic MR in LNSCO is different from the earlier reports. The second possible origin is the interaction between the magnetic field and magnetic domain or the pattern of the spin order. A fourfold symmetry due to this effect has been reported in the normal state of $Pr_{1.85}Ce_{0.15}CuO_4$ (Ref. 18) and $Y_{0.2}Pr_{0.8}Ba_2Cu_3O_{7-\delta}$.[19] According to the static stripe model, the doped carriers aggregate into charge stripes, while the background of CuO_2 plane outside is still antiferromagnetic; this arouses the possibility of a similar mechanism. Ando *et al.*[20] reported a twofold symmetric MR of ρ_c in the nonsupercondcuting $La_{1.99}Sr_{0.01}CuO_4$ single crystal which was associated with the antiferromagnetic order. However, the fourfold symmetry in our sample can be observed only below T_c^{onset}, indicating that its MR mechanism is different from that in $La_{1.99}Sr_{0.01}CuO_4$. It is probably due to the fact that the antiferromagnetic order in our samples is much weaker than that in $La_{1.99}Sr_{0.01}CuO_4$.[21,22] The third possibility responsible for the fourfold symmetry of c-axis MR in LNSCO is the interaction between the stripe phase and the vortices. Although the field is parallel to the ab plane of the crystal, Josephson vortices can jump across the CuO_2 planes in the form of vortex bundles[23] and form pancake vortices on the CuO_2 planes. Meanwhile, the slight mismatch between the field direction and the CuO_2 plane may also result in the formation of pancake vortices. The pancake vortices may distort and extend along the direction parallel to the stripe. Besides the pancake vortices, the segments of vortex lines can extend in the CuO_2 planes too because of the existence of weakly superconducting regions between charge stripes in CuO_2 planes. Both the pancake vortices and vortex line seg-

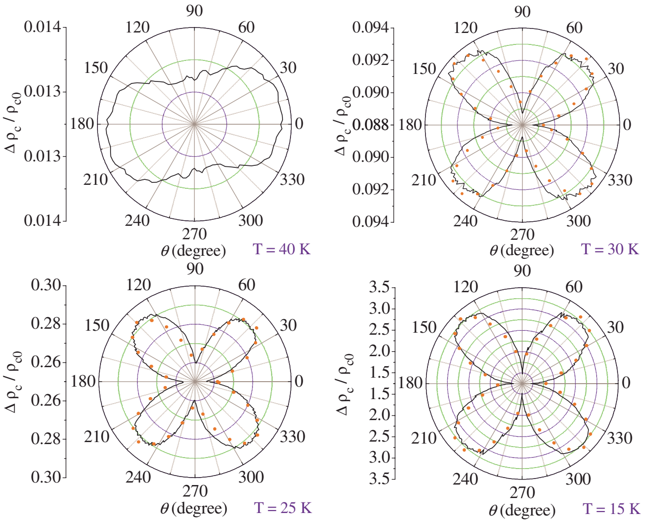

FIG. 2. (Color online) Angular dependences of the out-of-plane MR for x=0.15 under a magnetic field of 1 T at different temperatures. Dotted lines are the fittings using Eq. (1).

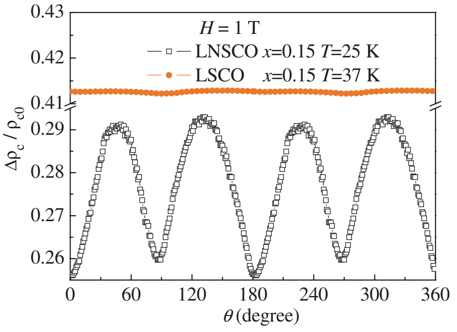

FIG. 3. (Color online) Comparison of the angular dependencies of MR in LSCO and LNSCO with x=0.15.

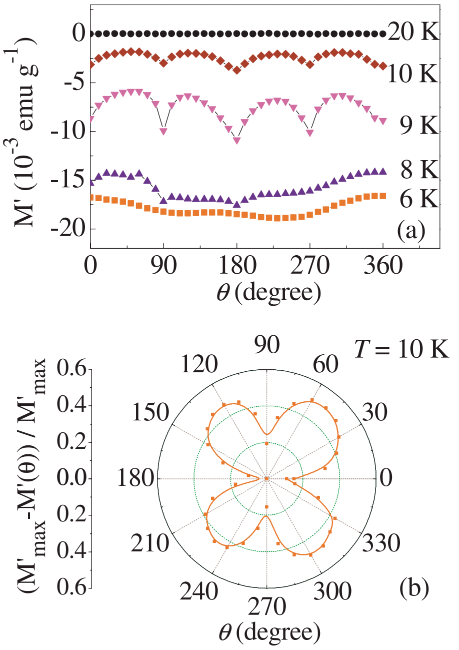

FIG. 4. (Color online) (a) Angular dependencies of M' of LNSCO $x=0.15$ sample at different temperatures and (b) a fourfold symmetry for M' at 10 K. The lines are guides for the eyes.

ments are intent to stay in the weakly superconducting region outside of the charge stripe.[7] As the direction of applied field is always perpendicular to the current, the Lorentz force will cause the movement of vortex along the direction parallel to the *ab* plane and perpendicular to the field. Because of the stripe structure, the movements of the pancake vortices and the vortex line segments are not arbitrary, and the vortex motion in the direction perpendicular to the stripe is restricted by the additional potential barrier which originates from the energy difference between the weakly and strongly superconducting regions due to the stripe phase. Therefore, the vortex movement is much more difficult in the direction perpendicular to the stripes than that along the stripes and the pining potential as well as the vortex movement in the CuO_2 are strongly dependent on the magnetic field direction.

The weakly superconducting regions due to the modulated superconductivity act as the intrinsic line pinning centers. This situation is similar to columnar defects which can provide a strong pinning potential to the flux lines along them.[24] The movement of the vortices will consume energy and lead to an increase in resistivity, while the stripe pinning effect can suppress the increase in resistivity by restraining the vortex movement. Consequently, this angular dependence of MR can give an evidence for the existence of the stripe structure in LNSCO. Similar to the $\rho \propto \sin^2\theta$ relation in the twofold symmetry,[20] the fourfold symmetry in LNSCO can be described as follows:

$$\Delta\rho_c/\rho_{c0} = a \sin^2 2\theta + b, \tag{1}$$

where a and b are constants. Equation (1) fits the anisotropic MR very well (see Fig. 2).

To convince the stripe pinning model mentioned above, the angular dependence of magnetization for LNSCO with

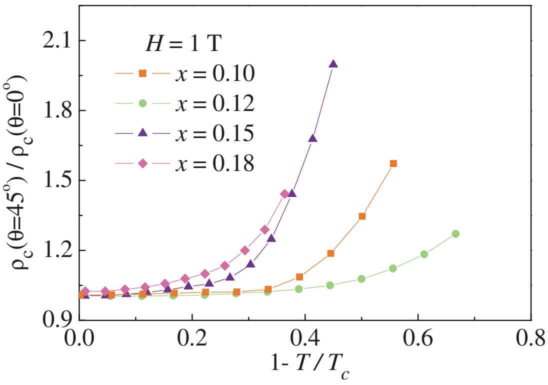

FIG. 5. (Color online) Anisotropic ratio $\rho_c(\theta=45°)/\rho_c(\theta=0°)$ of *c*-axis resistivities of LNSCO single crystals with different Sr contents under the in-plane magnetic field of 1 T.

$x=0.15$ under an in-plane magnetic field was measured. In order to exclude the influence of the magnetism of Nd ions,[10,25] the ac magnetization measurement mode was chosen. For each measurement, the dc magnetic field was fixed at 1 T and the ac magnetic field parallel to the dc field was applied with a fixed frequency ($f=100$ Hz) and amplitude ($H_{ac}=1$ Oe). Figure 4(a) shows the angular dependencies of the real part of magnetization (M') at different temperatures and Fig. 4(b) displays a fourfold symmetry for M' measured at 10 K, which is similar to the anisotropy in MR. The temperature dependence of the fourfold symmetry excludes the magnetic domains explanation since the anisotropic magnetization caused by magnetic domains should be observed for all the temperature range.[20,22] The angular dependence of the ac magnetization for LSCO $x=0.15$ crystal without a static stripe phase is also measured and the fourfold symmetry cannot be found. This suggests that the fourfold symmetry in M' of LNSCO originates from the vortex pinning by the static stripe phase. The pinning force of the stripe phase offers an additional resistance for the entrance of vortex line into the sample, according to the fact that the largest diamagnetism appears for the magnetic field parallel to stripe. The difference in the temperature range for the fourfold symmetry observed by two methods is due to the different characteristics between M' and resistivity.[26,27]

Figure 5 shows the Sr content dependence of the anisotropic resistivity in the form of $\rho_c(\theta=45°)/\rho_c(\theta=0°)$ under a magnetic field of 1 T for the LNSCO single crystals. The anisotropic magnitude for $x=0.12$ sample is the smallest among the four samples while the largest for $x=0.18$. Generally, the specimen for $x=0.12$ has the strongest static stripe phase as indicated by 1/8 anomaly.[28] One may regard that the stronger the stripe phase were, the larger the $\rho_c(\theta=45°)/\rho_c(\theta=0°)$ would be. However, the present result is opposite to this expectation. It is probably due to the stripe phase competing with the superconductivity and the enhancement in static stripe phase will weaken the superconductivity. Since the superconductivity is strongly suppressed near 1/8 doping,[29] the energy for a flux line to overcome the stripe structure will be reduced consequently. This result convinces us that the resistive anisotropy depends on both the superconductivity and the stripe-phase stability.

In conclusion, the fourfold symmetry of both the MR and the ac magnetization in $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ single crystals can be interpreted by the anisotropic flux pinning by the static stripe phase in this system. Furthermore, the magnitude of the anisotropy in MR of LNSCO single crystals shows a strongly doping as well as magnetic field dependence. The results imply that the anisotropic flux-pinning effect depends both on the stripe structure and on the superconductivity.

We acknowledge helpful discussions with Q. H. Chen of Zhejiang University. The work was supported by the NSFC (Grants No. 50721061 and No. 50832007) and the NBRPC (Grants No. 2006CB601003, No. 2006CB922005, and No. 2009CB929502).

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[1] Y. Ando, K. Segawa, S. Komiya, and A. N. Lavrov, Phys. Rev. Lett. **88**, 137005 (2002).

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

[3] V. Hinkov, D. Haug, B. Fauque, P. Bourges, Y. Sidis, A. Ivannov, C. Bernhard, C. T. Lin, and B. Kermer, Science **319**, 597 (2008).

[4] A. Gozar, B. S. Dennis, T. Siegrist, Y. Horibe, G. Blumberg, S. Komiya, and Y. Ando, Phys. Rev. B **68**, 052511 (2003).

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

[6] Q. Li, M. Hücker, G. D. Gu, A. M. Tsvelik, and J. M. Tranquada, Phys. Rev. Lett. **99**, 067001 (2007).

[7] M. Ichioka, M. Takigawa, and K. Machida, J. Phys. Soc. Jpn. **70**, 33 (2001).

[8] A. Grigorenko, S. Bending, T. Tamegai, S. Ooi, and M. Henini, Nature (London) **414**, 728 (2001).

[9] M. Connolly, S. J. Bending, A. N. Grigorenko, and T. Tamegai, Phys. Rev. B **72**, 224504 (2005).

[10] J. E. Ostenson, S. Bud'ko, M. Breitwisch, D. K. Finnemore, N. Ichikawa, and S. Uchida, Phys. Rev. B **56**, 2820 (1997).

[11] Y. Nakamura and S. Uchida, Phys. Rev. B **46**, 5841 (1992).

[12] X. Q. Xiang, J. F. Qu, Y. Q. Zhang, X. L. Lu, and X. G. Li, Mater. Sci. Forum **546-549**, 1897 (2007).

[13] K. Yamada, C. H. Lee, K. Kurahashi, J. Wada, S. Wakimoto, S. Ueki, H. Kimura, Y. Endoh, S. Hosoya, G. Shirane, R. J. Birgeneau, M. Greven, M. A. Kastner, and Y. J. Kim, Phys. Rev. B **57**, 6165 (1998).

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

[15] J. M. Tranquada, J. D. Axe, N. Ichikawa, Y. Nakamura, S. Uchida, and B. Nachumi, Phys. Rev. B **54**, 7489 (1996).

[16] T. Hanaguri, T. Fukase, Y. Koike, I. Tanaka, and H. Kojima, Physica B **165-166**, 1449 (1990).

[17] T. Naito, S. Haraguchi, H. Iwasaki, T. Sasaki, T. Nishizaki, K. Shibata, and N. Kobayashi, Phys. Rev. B **63**, 172506 (2001).

[18] P. Fournier, M.-E. Gosselin, S. Savard, J. Renaud, I. Hetel, P. Richard, and G. Riou, Phys. Rev. B **69**, 220501(R) (2004).

[19] V. Sandu, C. Zhang, C. C. Almasan, B. J. Taylor, and M. B. Maple, J. Phys.: Conf. Ser. **51**, 231 (2006).

[20] Y. Ando, A. N. Lavrov, and S. Komiya, Phys. Rev. Lett. **90**, 247003 (2003).

[21] G. Aeppli, T. E. Mason, S. M. Hayden, H. A. Mook, and J. Kulda, Science **278**, 1432 (1997).

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

[23] S. Chakravarty, B. I. Ivlev, and Y. N. Ovchinnikov, Phys. Rev. Lett. **64**, 3187 (1990).

[24] C. Dasgupta and O. T. Valls, Phys. Rev. B **66**, 064518 (2002).

[25] J. F. Ding, X. Q. Xiang, Y. Q. Zhang, H. Liu, and X. G. Li, Phys. Rev. B **77**, 214524 (2008).

[26] T. T. M. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. B **41**, 6621 (1990).

[27] J. Deak, M. McElfresh, John R. Clem, Zhidong Hao, M. Konczykowski, R. Muenchausen, S. Foltyn, and R. Dye, Phys. Rev. B **47**, 8377 (1993).

[28] A. R. Moodenbaugh, L. H. Lewis, and S. Soman, Physica C **290**, 98 (1997).

[29] N. Ichikawa, S. Uchida, J. M. Tranquada, T. Niemöller, P. M. Gehring, S.-H. Lee, and J. R. Schneider, Phys. Rev. Lett. **85**, 1738 (2000).