PHYSICAL REVIEW B **77**, 214524 (2008)

# Two-dimensional superconductivity in stripe-ordered $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ single crystals

J. F. Ding, X. Q. Xiang, Y. Q. Zhang, H. Liu, and X. G. Li*
*Hefei National Laboratory for Physical Sciences at Microscale, Department of Physics,*
*University of Science and Technology of China, Hefei 230026, People's Republic of China*
*and International Center for Materials Physics, Academia Sinica, Shenyang 110015, China*

(Received 3 February 2008; revised manuscript received 18 April 2008; published 26 June 2008)

The dc and ac magnetizations of the stripe-ordered $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ ($x=0.10,0.15,0.18$) single crystals have been studied systematically under different magnetic-field orientations. It is found that the dc magnetizations $M$ for all the three different doped samples show two diamagnetic steps for $H\parallel c$, while there is only one for $H\parallel ab$. The real part $M'$ of the ac magnetization is similar to that of the dc one and the imaginary part $M''$ shows two peaks at the temperatures corresponding to the two steps of $M'$. For comparison, the dc magnetization of $La_{1.85}Sr_{0.15}CuO_4$ single crystal without static stripe phase has only one transition for $H\parallel c$. The results suggest that the anisotropic magnetic properties in $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ are closely related to the decoupling between the $CuO_2$ planes by the static stripe order which causes a two-dimensional superconducting state in the system.

DOI: 10.1103/PhysRevB.77.214524

PACS number(s): 74.25.Ha, 74.25.Qt, 74.72.Dn

## I. INTRODUCTION

It is known that the vortex dynamics is one of the most important topics in the field of high-transition temperature ($T_c$) superconductivity. Due to the short coherence and layered structure in high-$T_c$ superconductors, thermal and quantum fluctuations as well as quenched disorders give rise to some new vortex phases and properties, such as vortex glass, vortex liquid, vortex entanglement, and dimensional crossover three-dimensional (3D)-two–dimensional (2D) etc.[1–3] In the studies of vortex phase, some of high-$T_c$ superconductors have two transitions or two peaks in the magnetization curves. For example, in $Bi_2Sr_2Ca_{1-x}Gd_xCu_2O_8$ single crystals, the decoupling of $CuO_2$ interlayers induced by external magnetic fields can cause two magnetic transitions in dc magnetic fields.[4] In $YBa_2Cu_3O_{7-\delta}$ (Ref. 5) and $Pr_{0.88}LaCe_{0.12}CuO_{4-\delta}$ (Ref. 6) systems, the appearances of two peaks in the imaginary part of ac magnetization have usually been regarded as due to the multiple flux phase transitions. While in the $Bi_2Sr_{2-x}LaCuO_{6+y}$ (Ref. 7) and the overdoped $La_{2-x}Sr_xCuO_4$ (Ref. 8) single crystals, two transitions in the dc magnetization are related to the appearance of superconducting clusters and the Josephson coupling among them, respectively. Recently, Li *et al.*[9] observed a crossover from normal state to 2D superconducting state with decreasing temperature in a stripe-ordered $La_{1.875}Ba_{0.125}CuO_4$ single crystal. The 2D superconducting state existed at a temperature higher than the bulk $T_c$ suggests that the dominant impact of the stripe order is to electronically decouple the $CuO_2$ planes, which results in a suppression of the bulk $T_c$. Furthermore, the earlier study on the angle-resolved photoemission and scanning tunneling spectroscopies of the stripe-ordered $La_{1.875}Ba_{0.125}CuO_4$ system revealed a *d*-wave-like gap at low temperature, and suggested that a superconducting phase has already formed above the bulk $T_c$ (Ref. 10). Therefore, if there truly exists a 2D superconductivity in the $CuO_2$ plane for a stripe-ordered high-$T_c$ material, one may observe a two steplike transition in the dc magnetization and two peaks in the imaginary part of the ac magnetization for magnetic fields that are perpendicular to the $CuO_2$ plane. This implies that the 2D superconductivity in a stripe-ordered system can cause some anisotropic magnetic properties, and a diamagnetic signal for the 2D superconductivity will appear at a temperature higher than the bulk $T_c$.[9]

Despite the intensive investigations of the superconductivity in the stripe-ordered $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ system, there is still no experimental evidence for the existence of the 2D superconductivity in the system. In this paper, a clear evidence for a 2D superconductivity is presented from the magnetic properties of $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ single crystals. Although the 2D superconducting transition temperature is higher than the bulk $T_c$, it is still lower than the $T_c$ of $La_{2-x}Sr_xCuO_4$ single crystal without static stripe phase for the same Sr content, which reflects an intrinsic property of the static stripe phase in $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ single crystals.

## II. EXPERIMENTS

The single crystals are grown by a traveling solvent floating-zone technique.[11,12] The crystals for the present measurements are shaped into platelets with dimensions of $3.0\times1.0\times0.7$ mm$^3$, with the shortest edge parallel to the *c* axis. The structure of the crystal is characterized by a high-resolution x-ray diffraction (XRD) technique (Philips X'Pert Pro diffractometer). The in-plane resistivity is measured using a standard four-probe method. The dc and ac magnetizations are studied using a superconducting quantum interference device (SQUID) (Quantum Design, MPMS-XL). The field-cooled dc magnetizations are measured as a function of temperature at a constant field of 1 Oe. For each ac measurement, the ac magnetic field is parallel to the dc field with a fixed frequency ($\nu=100$ Hz) and amplitude ($H_{ac}=1$ Oe). The dc magnetic field is applied at 100 K, then the sample is cooled to 2 K without ac magnetic field, and finally the ac magnetic field is superimposed and the data are collected in the warming process.

## III. RESULTS AND DISCUSSION

The XRD result of $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ in Fig. 1(a) shows that the crystal is of a pure phase. In Fig. 1(b), the

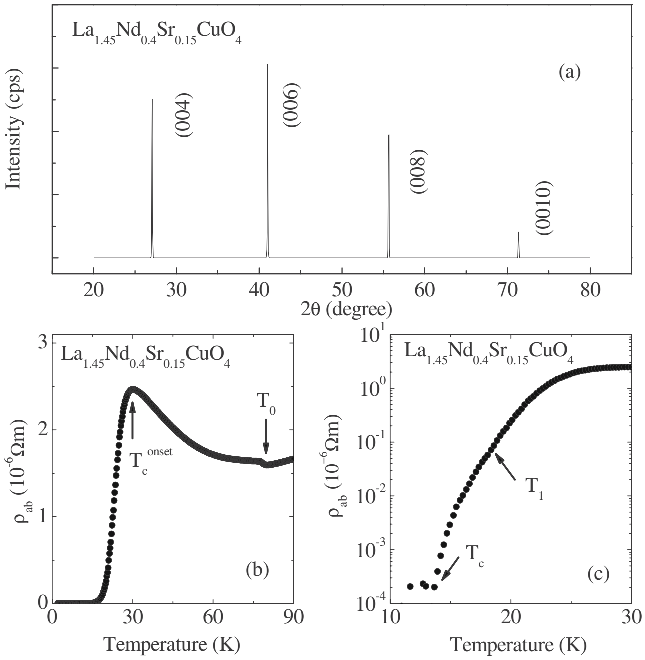

FIG. 1. (a) X-ray diffraction pattern for $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ single crystal. Temperature dependence of the in-plane resistivity is shown in different coordinate systems: (b) rectangular coordinate and (c) semilogarithmic coordinate.

in-plane resistivity under zero field shows a jump at about $T_0=77$ K, which corresponds to the structural phase transition from the low-temperature orthorhombic to the low-temperature tetragonal phase.[11,13] The onset superconducting transition temperature $T_c^{\text{onset}}$ and the zero resistance temperature $T_c$ are about 30 and 13.6 K, respectively, and a weak trace of a shoulder appears around 19 K, as shown in Fig. 1(c). It may imply that there exist two superconducting transitions in the system. To further clarify the nature of this phenomenon, the magnetizations of the system are studied. The temperature dependencies of the dc magnetizations of the three different doped samples $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ ($x=0.10, 0.15, 0.18$) for magnetic fields parallel and perpendicular to the $CuO_2$ plane exhibit anisotropic diamagnetic behaviors, as shown in Fig. 2. The magnetization shows one diamagnetic step for magnetic fields parallel to the $CuO_2$ plane ($H \| ab$), while it has two steps for the fields perpendicular to the planes ($H \| c$). For the optimally doped sample $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$, the two steps clearly appear at $T_1=21$ K and $T_2=13.6$ K for $H \| c$, respectively, as shown in Fig. 2(b). It is noted that the superconducting transition temperature for $H \| ab$ is very close to $T_2$. For comparison, the dc magnetization of $La_{1.85}Sr_{0.15}CuO_4$ single crystal without the static stripe phase has only one transition for $H \| c$, as shown in Fig. 2(d). Therefore, the two transitions in $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ single crystals might be the intrinsic property caused by the static stripe phase of the system.

It should be noted that in our experiments, the two transitions observed at a very low magnetic field of 1 Oe are different from the previous reports of two transitions in the dc magnetization curve for many other superconductors.[4,7,8] In their reports, the two transitions originated from the flux phase transition or the decoupling between $CuO_2$ planes[4] usually occur at high magnetic fields.[5,6] Furthermore, although the two transitions in $Bi_2Sr_{2-x}LaCuO_{6+y}$ (Ref. 7) and $La_{2-x}Sr_xCuO_4$ (Ref. 8) caused by the 3D superconducting clusters and the Josephson coupling among them can also appear at a low magnetic field, they should be observed for both magnetic fields parallel and perpendicular to the $CuO_2$ plane. Therefore, one can regard that the two diamagnetic steps in our experiments are probably due to two superconducting transitions and can be explained using a 2D superconducting fluctuation model, which was reported recently by Berg *et al.*[14] According to this model, the static stripe phase will cause the decoupling between $CuO_2$ planes and result in a suppression of the bulk $T_c$. Thus, there is a separation between superconducting transition temperature in the $CuO_2$ plane and interlayer coupling temperature among the

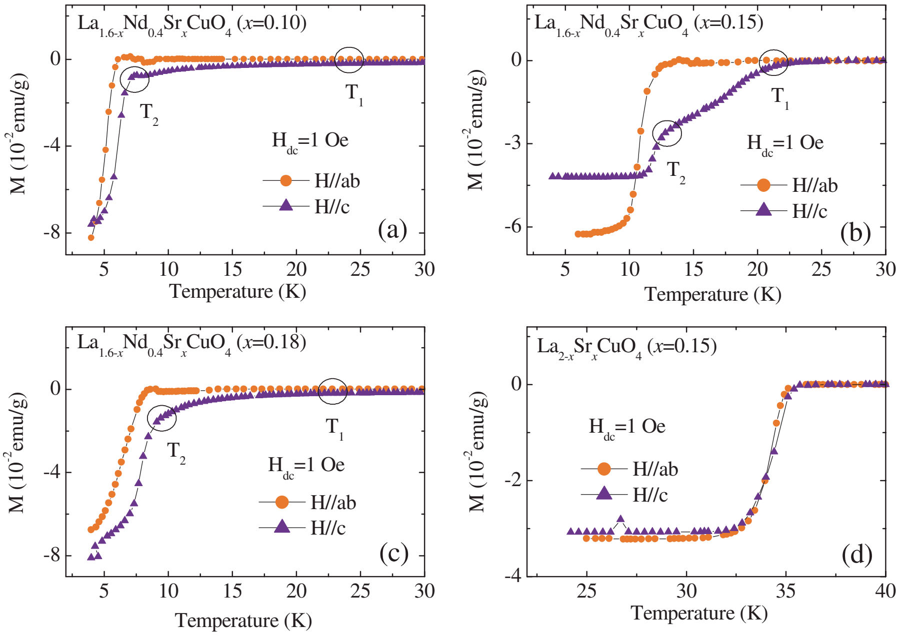

FIG. 2. (Color online) Temperature dependencies of the field-cooled dc magnetizations for $H_{dc} \| ab$ plane and $H_{dc} \| c$ axis at a constant field of 1 Oe. (a) $La_{1.50}Nd_{0.4}Sr_{0.10}CuO_4$, (b) $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$, (c) $La_{1.42}Nd_{0.4}Sr_{0.18}CuO_4$, and (d) $La_{1.85}Sr_{0.15}CuO_4$.

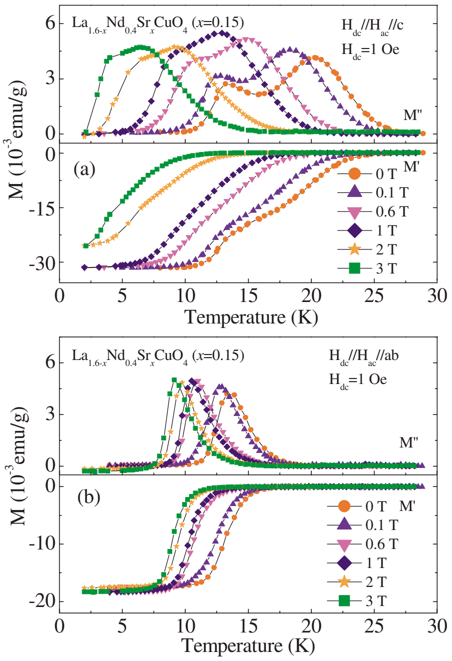

FIG. 3. (Color online) Temperature dependencies of ac magnetizations $M=M'+i\,M''$ at different $H_{dc}$ varying from 0 to 3 T. (a) $H_{dc}\|H_{ac}\|c$ axis and (b) $H_{dc}\|H_{ac}\|ab$ plane.

planes, and the sample will show two superconducting transitions as a result. It implies that in $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$, the high-temperature transition is attributed to the appearance of superconductivity in the $CuO_2$ plane, and the other one is due to the Josephson coupling between the $CuO_2$ planes.

In order to study the 2D superconductivity in $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ more clearly, the ac magnetizations are measured. As we know, the real part $(M')$ in ac magnetization corresponds to the screening current properties of the sample and the imaginary part $(M'')$ represents the energy dissipation of the vortices.[15] Figure 3 shows the ac magnetizations of the optimal doped $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ in different dc magnetic fields. It can be seen that $M''$ has two peaks accompanied with two steplike transitions in $M'$ for $H\|c$, while there is only one peak for $H\|ab$. With increasing magnetic fields, the positions of the two peaks decrease monotonously to lower temperatures and close to each other because the high-temperature peak position decreases more quickly. For $H_{dc}=0$, the variation of $M'$ is very similar to that of dc magnetization in Fig. 2(b), and the transition temperatures measured in the two different ways are almost the same. This result cannot be interpreted in the framework of multiple flux phase transitions,[5,6,16] such as the melting of flux-line lattice, the melting, decoupling, and/or depinning of the two-dimensional pancake vortices. The reason is that all the multiple flux phase transitions do not occur under a zero dc magnetic field. With reference to the dc result, it is further confirmed that the high-temperature transition step in $M'$ together with the corresponded peak in $M''$ is related to the 2D superconductivity in the $CuO_2$ plane and the low temperature one is probably due to the Josephson coupling between $CuO_2$ planes.

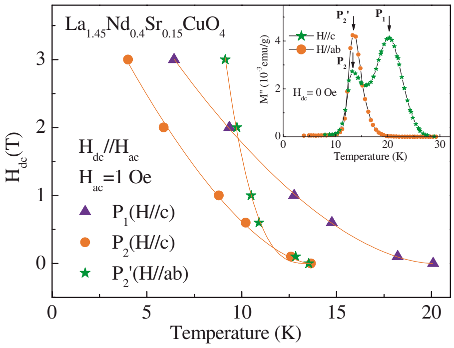

FIG. 4. (Color online) Relationship between dc magnetic fields and temperatures of the magnetization peaks for $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$. The lines are the fittings using Eq. (1). The inset shows the peak labels and the lines are the guides for eyes.

The peak temperatures under different dc magnetic fields for $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ obtained from Fig. 3 are shown in Fig. 4. In the inset of Fig. 4, the high- and low-temperature peaks are named as $P_1$ and $P_2$, respectively, for $H\|c$, while for $H\|ab$ there is only one peak named as $P_2'$. The temperatures of the three peaks are all decreasing with increasing magnetic fields. As we know, a peak position in an imaginary part of ac magnetization represents its irreversibility point.[17] The irreversibility line $H_{irr}(T)$ is the boundary line that separates the vortex liquid state from the vortex solid state.[18] By crossing $H_{irr}(T)$ from lower toward higher temperatures, the vortex lattice undergoes a melting and depinning transition.[19] The temperature dependence of the irreversibility field $H_{irr}$ can be fitted according to the formula[19]

$$H_{irr}(T)=H_0[1-T_{irr}(H)/T_{irr}(0)]^{\upsilon}. \tag{1}$$

Here, $\upsilon$ and $H_0$ are the fitting parameters. The temperature dependencies for the three peaks can be fitted well using Eq. (1) with fitting parameters listed in Table I, as shown in Fig. 4. The fitting result of $P_1$ suggests that the pancake vortices in the $CuO_2$ plane undergo a crossover from 2D vortex solid state to 2D vortex liquid state at the irreversibility line for $P_1$ (Ref. 20). The fittings for $P_2$ and $P_2'$ represent the irreversibility lines corresponding to the bulk superconductivity for fields perpendicular and parallel to the $CuO_2$ plane, respectively.[17] With increasing dc fields, the temperature of $P_1$ $(T_{P1})$ decreases more quickly than that of $P_2$ $(T_{P2})$ as the pinning force for 2D pancake vortices without interlayer Josephson coupling is weaker than that for the vortex lines.[21,22] It is worth mentioning that as compared with the previously results reported by Ostenson *et al.*,[23] in which the dc $M$-$H$ curve of $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ for magnetic field perpendicular to the $CuO_2$ plane was investigated, the irreversibility

TABLE I. The fitting parameters $\upsilon$ and $H_0$ for Eq. (1).

| *Peak* | $\upsilon$ | $H_0$ (*T*) | $T_{irr}(0)$ (K) |
|---|---|---|---|
| $P_1$ | 1.732 | 5.864 | 20.09 |
| $P_2$ | 1.611 | 5.173 | 13.65 |
| $P_2'$ | 2.963 | 84.50 | 13.53 |

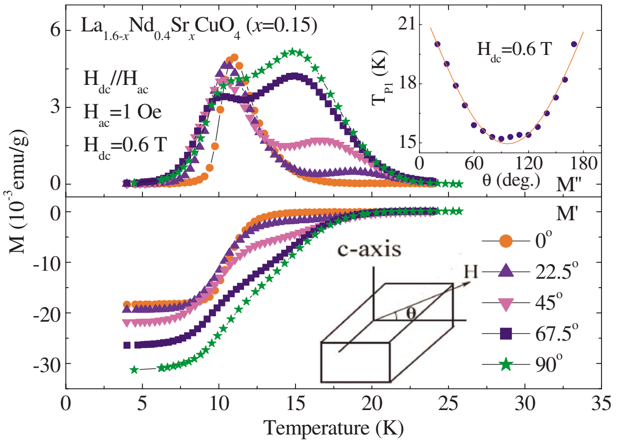

FIG. 5. (Color online) Temperature dependencies of the ac magnetizations at different angles between the external magnetic field and the $CuO_2$ plane at $H_{dc}=0.6$ T. The inset is the angular dependence of $T_{P1}$ (the temperature of $P_1$) at $H_{dc}=0.6$ T and the line is the fitting by Eq. (2).

line in our experiments shifts to the high temperature and high-field region. The discrepancy in measuring the irreversibility line may be a result of using different methods.[24] Since $P_1$ disappears for $H \| ab$, one may want to know whether it means the 2D superconductivity can be observed only for $H \| c$. Thus, the magnetization measurements at different magnetic-field orientations are presented below.

The ac magnetizations of $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ under different magnetic-field orientations change regularly from $\theta=0°$ to $\theta=90°$, where $\theta$ is the angular for the magnetic field rotated from *ab* plane to *c* axis, as shown in Fig. 5. One can see that $P_1$ cannot be detected for $H \| ab$ ($\theta=0°$), but it becomes more and more notable with increasing $\theta$ and gets its maximum at $H \| c$ ($\theta=90°$). In the inset of Fig. 5, $T_{P1}$ shows a twofold symmetry with respect to the angular. Usually this twofold symmetry means that the flux structure is determined by only one directional component of magnetic field,[16] so a simple trigonometric function is used to fit the angular dependence of $T_{P1}$ as follows:

$$T_{P1}(\theta) = k \cos(\theta + 90°) + T_0, \tag{2}$$

where $k$ is a constant and $T_0$ is the maximum value of $T_{P1}$. This equation fits experimental results very well, as shown in the inset of Fig. 5. Thus, one can regard that the 2D superconducting transition phenomenon is out-of-plane magnetic-field component dependent. The angular dependencies of $T_{P1}$ for the four different magnetic fields in Fig. 6 are similar to the inset of Fig. 5 and can also be fitted using Eq. (2). In Fig. 6, the value of $T_{P1}(\theta=0°)$ extrapolated from the fittings almost remains unchanged for fields lower than 1 T. The fitting results for $P_1$ suggests that the 2D superconducting transition temperature in the $CuO_2$ plane is almost independent of magnetic fields below 1 T which is parallel to the $CuO_2$ plane. Because magnetic fields parallel to the planes will generally reduce the coherent length of *c* axis and cause the decoupling between $CuO_2$ planes,[25] one can regard that this 2D superconducting transition temperature is $CuO_2$ plane decoupling independent.

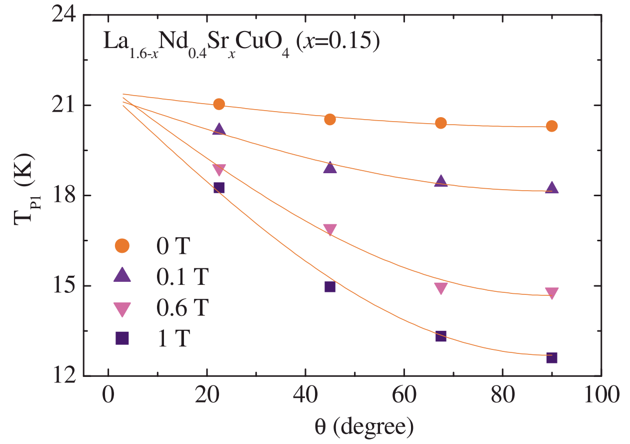

FIG. 6. (Color online) Angular dependence of $T_{P1}$ (the temperature of $P_1$) at different $H_{dc}$ varying from 0 to 1 T and the lines are the fittings using Eq. (2).

Additionally, it should be noted that although Nd substitution induces the static stripe phase into the system without changing the doped carrier density when Sr content keeps as a constant,[26] the 2D superconducting transition temperature $T_1$ of the stripe-ordered $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ system is lower than the $T_c$ of $La_{1.85}Sr_{0.15}CuO_4$. This is possibly due to the following two reasons. First, a long-range periodic lattice distortion induced by Nd substitution in $La_{1.85-y}Nd_ySr_{0.15}CuO_4$ system will pin down the static stripe and suppress the superconducting order in the $CuO_2$ planes.[27] Second, the disorder induced by Nd substitution on the cation site residing outside the $CuO_2$ planes can also lead to the suppression of superconductivity.[28] Further detailed investigations need to be carried out to clarify the relationship between the 2D superconductivity and the static stripe phase in the future.

## IV. SUMMARY

A particular 2D superconductivity, which is closely related to the decoupling between $CuO_2$ planes caused by static stripe phase, is revealed by investigating the dc and ac magnetizations for $H \| ab$ and $H \| c$ in the stripe-ordered $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ single crystals. This 2D superconductivity occurred at a temperature higher than the bulk $T_c$ which suggests that the decoupling is one of the most important facts for the suppression of $T_c$ by static stripe phase. However, the 2D superconducting transition temperature is almost independent of the decoupling between $CuO_2$ planes in magnetic fields below 1 T.

## ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (Contract No. 50721061) and the National Basic Research Program of China (Contracts No. 2006CB601003 and No. 2006CB922005).

*Corresponding author; lixg@ustc.edu.cn

[1] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

[2] M. C. Miguel and S. Zapperi, Nat. Mater. **2**, 477 (2003).

[3] H. Beidenkopf, N. Avraham, Y. Myasoedov, H. Shtrikman, E. Zeldov, B. Rosenstein, E. H. Brandt, and T. Tamegai, Phys. Rev. Lett. **95**, 257004 (2005).

[4] X. G. Li, X. Zhao, X. J. Fan, X. F. Sun, W. B. Wu, and H. Zhang, Appl. Phys. Lett. **76**, 3088 (2000).

[5] J. Giapintzakis, R. L. Neiman, D. M. Ginsberg, and M. A. Kirk, Phys. Rev. B **50**, 16001 (1994).

[6] Y. Wang, C. Ren, L. Shan, S. L. Li, P. C. Dai, and H. H. Wen, Phys. Rev. B **75**, 134505 (2007).

[7] H. H. Wen, W. L. Yang, Z. X. Zhao, and Y. M. Ni, Phys. Rev. Lett. **82**, 410 (1999).

[8] H. H. Wen, X. H. Chen, W. L. Yang, and Z. X. Zhao, Phys. Rev. Lett. **85**, 2805 (2000).

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

[10] T. Valla, A. V. Federov, J. Lee, J. C. Davis, and G. D. Gu, Science **314**, 1914 (2006).

[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] S. Wakimoto, R. J. Birgeneau, Y. Fujimaki, N. Ichikawa, T. Kasuga, Y. J. Kim, K. M. Kojima, S.-H. Lee, H. Niko, J. M. Tranquada, S. Uchida, and M. v. Zimmermann, Phys. Rev. B **67**, 184419 (2003).

[14] E. Berg, E. Fradkin, E.-A. Kim, S. A. Kivelson, V. Oganesyan, J. M. Tranquada, and S. C. Zhang, Phys. Rev. Lett. **99**, 127003 (2007).

[15] N. Morozov, E. Zeldov, D. Majer, and M. Konczykowski, Phys. Rev. B **54**, R3784 (1996).

[16] C. Duran, J. Yazyi, F. de la Cruz, D. J. Bishop, D. B. Mitzi, and A. Kapitulnik, Phys. Rev. B **44**, 7737 (1991).

[17] A. P. Malozemoff, T. K. Worthington, Y. Yeshurun, F. Holtzberg, and P. H. Kes, Phys. Rev. B **38**, 7203 (1988).

[18] Y. Liu and X. G. Li, J. Appl. Phys. **99**, 053903 (2006).

[19] G. Blatter and B. Ivlev, Phys. Rev. Lett. **70**, 2621 (1993).

[20] N.-C. Yeh, Phys. Rev. B **40**, 4566 (1989).

[21] P. Minnhagen, Rev. Mod. Phys. **59**, 1001 (1987).

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

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

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

[25] X. Hu and M. Tachiki, Phys. Rev. B **70**, 064506 (2004).

[26] J. M. Tranquada, N. Ichikawa, and S. Uchida, Phys. Rev. B **59**, 14712 (1999).

[27] K. Fujita, T. Noda, K. M. Kojima, H. Eisaki, and S. Uchida, Phys. Rev. Lett. **95**, 097006 (2005).

[28] J. P. Attfield, A. L. Kharlanov, and J. A. McAllister, Nature (London) **394**, 157 (1998).