Competition of Static Stripe and Superconducting Phases in $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ Controlled by Pressure

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We have investigated the pressure effect on T_c and the Hall coefficient in the static stripe-ordered phase of $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ crystal under hydrostatic pressure. We found a dramatic change of the Hall coefficient and an abrupt increase of T_c at low pressure of about 0.1 GPa. The results are indicative of a transition from one- to two-dimensional charge transport, associated with the suppression of low-temperature-tetragonal (LTT) phase. From the uniaxial pressure measurements it turns out that the observed critical change is induced primarily due to the in-plane compression of the CuO_2 planes which would make the pinning potential of the LTT lattice distortions weaker.

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The uniqueness of the stripes in cuprates is that they might intimately be related to high critical temperature (high-T_c) superconductivity [1,2]. The inelastic neutron experiments have recently revealed incommensurate spin modulation in representative high-T_c cuprates [3,4]. This suggests the coexistence of dynamical stripes with superconductivity on the same CuO_2 planes. It is still under debate whether stripes promote or suppress high-T_c superconductivity. In La-based cuprates $La_{2-x}Sr_xCuO_4$ (LSC), the stripes become static by partial substitution of Nd for La [5], without changing the doped hole density. The formation of static stripes are associated with the structural transformation from the orthorhombic (LTO) to low-temperature-tetragonal (LTT) phases which involve distortions of CuO_2 planes due to the tilt of CuO_6 octahedra producing stripe pinning potential [5,6]. This is also the case with the $La_{2-x}Ba_xCuO_4$ system at a particular composition $x = 1/8$ [7]. In the static stripe phase T_c is radically reduced, and in this regard the static stripes are destructive to high-T_c superconductivity (essentially a competitor of high-T_c superconductivity).

The static stripes in the cuprates are quite distinct from those in other transition-metal oxides such as nickelates [8] and manganites [9] in that the stripes are conductive in cuprates. They are one-dimensional (1D) metallic for $x \leq 1/8$ [10], and probably coexist with superconducting (SC) order for $x > 1/8$ [11]. Moreover, the diffraction experiment gives evidence for the glassy nature of cuprate stripes [12], indicating that the stripes are only weakly pinned by the LTT distortions and that the competition between SC and the stripes may be controllable rather easily by external perturbations. It is of fundamental importance both in basic and possible applicational researches to search for control parameters which suppress (promote) static stripe order and thus enhance (reduce) SC transition temperature. Nd or Eu substitution for La is the best known control parameter. At a critical rare-earth (RE) substitution, the LTT distortion switches on in a first order transition, jumping from the SC regime to the stripe-dominated regime. Substitution of Zn for Cu or application of magnetic fields is believed to stabilize stripes [13,14]. A practical problem with magnetic fields is that one needs intense fields of ~50 T, and Zn introduces quenched disorder, adding more complexities to the problem. These perturbations, including RE substitution, are "one way" control parameters, stabilizing stripes, not enhancing the SC order.

In this paper, we demonstrate that pressures that exert the in-plane strains most effectively control the competing stripe and SC orders. The transport measurements on the static stripe phase of $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ under hydrostatic and uniaxial pressures reveal that in-plane compression of ~0.1 GPa is enough for the high-T_c SC phase to be more stable than the stripe phase.

Single crystals of $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ (LNSC) were grown by the traveling-solvent floating-zone method [15]. The compositions of grown crystals are almost identical to those of the ones previously characterized by the neutron scattering study [5]. They were also confirmed by the electron-probe microscopic analysis as well as by the LTO-LTT transition temperature ($T_d \sim 68$ K) and the suppressed T_c (T_c of Nd-free LSC is about 27 K).

Resistivity was measured by the standard dc four-probe method with gold paste attached as electrodes, which were annealed under flowing oxygen atmosphere at 900 °C for a few hours in order to reduce contact resistance. The Hall coefficient was measured in the magnetic field of 4 T applied parallel to the c axis. For the measurements under

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hydrostatic pressures (P), a piston-cylinder Teflon pressure cell was used with fluorinert liquid No. 70 as a pressure medium. The magnitude of pressure was calibrated using the method described in Ref. [16] and kept constant at low temperatures to within 3%. Nearly isotropic pressure was applied to the sample even when the fluorinert liquid was frozen at low temperatures as long as P is lower than 1 GPa in view of the previous works using the same setup [16]. Samples were polished in a thin rectangular plate with a thickness of 150 μm. The uniaxial pressure was applied along the in-plane and c-axis directions. The details of the experimental setup were reported elsewhere [17].

The temperature (T) dependences of the in-plane resistivity (ρ_{ab}) and Hall coefficient of LNSC under various hydrostatic pressures are shown in Figs. 1(a) and 1(b), respectively. The resistivity does not change up to 0.13 GPa; it shows two characteristic temperatures, T_c (~8 K) and T_d (~68 K) at which a small resistivity jump is seen. When P exceeds 0.13 GPa, T_c abruptly goes up [T_c is more than doubled as illustrated in Fig. 1(c)] and the resistivity jump at T_d becomes hardly seen, indicating that the LTT phase is suppressed. Beyond $P = 0.2$ GPa, T_c steadily increases at a rate of $dT_c/dP \sim +19$ K/GPa.

The P dependence of the Hall coefficient (R_H) is more dramatic than that of resistivity. At ambient P, R_H shows a characteristic change in the LTT phase below T_d [10]. This is interpreted by supposing that the charge carriers are confined in each 1D stripe and that the carriers cannot hop between stripes. In this case we expect that the off-diagonal conductivity vanishes and consequently the Hall coefficient tends to be zero [10]. As in the case of resistivity, R_H (T) also does not essentially change up to $P = 0.1$ GPa. A remarkable change happens when P is increased to 0.2 GPa. R_H measured at 0.2 GPa does not show any sharp change above T_c, restoring finite values even at low enough temperatures and showing a broad peak at $T \sim 60$ K like that in Nd-free LSC [18]. In this regard, the result demonstrates a transition (or a rapid crossover) from one- to two-dimensional (2D) charge transport regime when P exceeds 0.1 GPa. Similar transition (or crossover) is observed for $\mathrm{La}_{2-x-y}\mathrm{Nd}_y\mathrm{Sr}_x\mathrm{CuO}_4$ ($y = 0.6$) when x increases beyond 1/8 [10].

The recovery of R_H at low temperatures under pressure indicates that the confinement of charge carriers within charge stripes is relaxed due to weakening of pinning potential. This is in conjunction with the suppression of the LTO-LTT transition as evidenced from what is happening in ρ_{ab} (T) around T_d with an increase of P. Therefore, the result in Fig. 1 also demonstrates a pinning-depinning transition occurring at a pressure between 0.1 and 0.2 GPa. Above 0.2 GPa, i.e., in the LTO phase, R_H does not change any more, in agreement with the P-independent R_H for LSC in the SC regime (the LTO phase) [16].

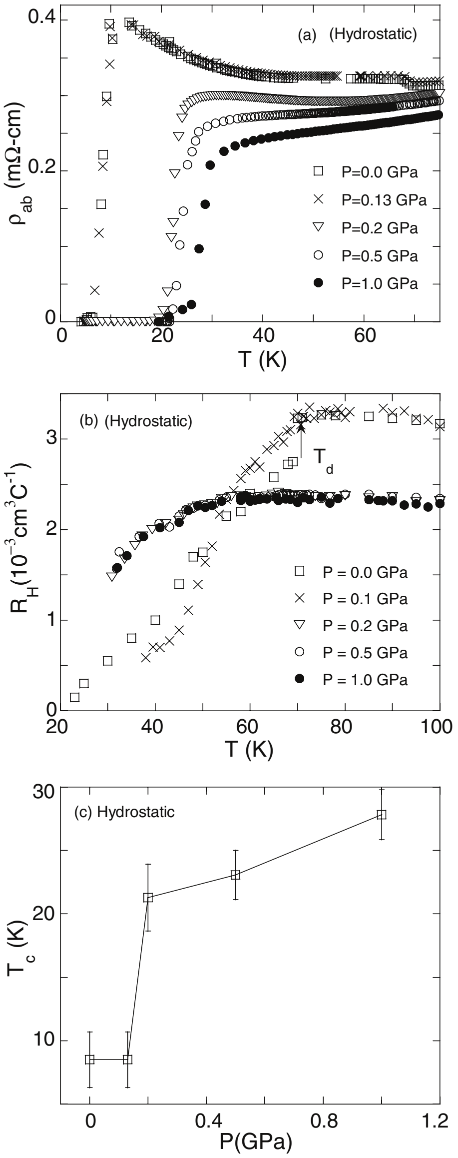

FIG. 1. (a) Temperature dependence of the in-plane resistivity for $\mathrm{La}_{1.48}\mathrm{Nd}_{0.4}\mathrm{Sr}_{0.12}\mathrm{CuO}_4$ under various hydrostatic pressures. (b) The Hall coefficient plotted as a function of T at various hydrostatic pressures. (c) Plot of T_c vs pressure. The error bar to T_c corresponds to the temperatures at which the resistivity drops to 90% and 10% of the value just above the onset.

As LNSC, as well as other high-T_c cuprates, are strongly anisotropic media, it is of crucial importance to determine which pressure component, parallel or perpendicular to the planes, is more effective in producing such a dramatic effect. The uniaxial pressure effects are displayed in Figs. 2(a) and 2(b). Figure 2(a) shows the T dependences of the c-axis resistivity (ρ_c) under compressive pressure applied parallel to the a-b plane, and the c-axis resistivity under c-axis compression is shown in Fig. 2(b). In order to apply sufficiently high uniaxial pressures and to make the pressure uniform, the surfaces of both sides of a sample need to be as parallel as possible and also have the cross section and the length of sample as small as possible. Because of these requirements we had to restrict ourselves to the c-axis resistivity measurement under uniaxial

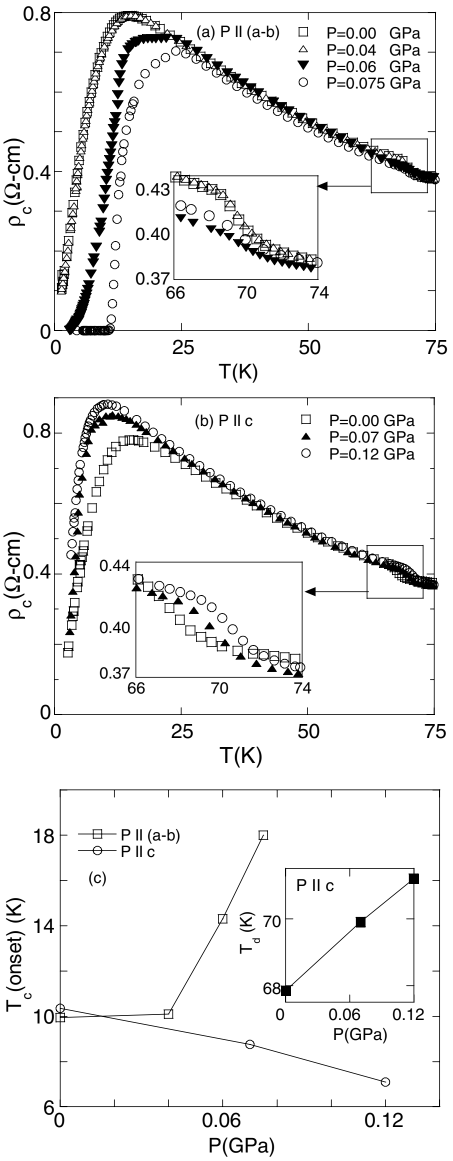

FIG. 2. Temperature dependence of the c-axis resistivity measured for $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ under uniaxial pressure (a) along the a-b plane direction and (b) along the c axis [insets: close-up of ρ_c (T) near the LTO-LTT transition at $T_d \sim 70$ K]. The difference in the magnitude of ρ_c between these two plots arises mainly from fairly large uncertainty in the distance between the contacts for voltage electrodes. (c) Onset T_c plotted as a function of a-b (squares) and c-axis (circles) pressure. T_c is defined at temperature where ρ_c drops to 90% of the peak value. The inset shows T_d vs P_c plot for the c-axis pressure. T_d is determined at a midpoint of the steplike curve shown in the inset of (b). T_d is ill-defined for the in-plane pressure, since the feature at T_d becomes broad above 0.04 GPa.

pressures and use crystals cut from different parts of the same batch for measurements in different pressure/contact (for resistivity) configurations. Incidentally, T_c values of the two crystals used for the uniaxial-pressure measurements are lower due to fluctuations of Sr and/or Nd contents than that used for the hydrostatic pressure measurements, and the SC transition is so broad that ρ_c does not reach zero above 2 K.

As demonstrated in Ref. [15], ρ_c and ρ_{ab} of LNSC ($x = 0.12$) show basically the same response at T_c and T_d. Therefore, we expect that the comparison between ρ_c for uniaxial pressure and ρ_{ab} for hydrostatic pressure makes sense, as long as we are concerned with the pressure dependence of T_c and T_d.

The contrasting behavior is evident. T_c remarkably increases for the a-b pressure (P_a) [Fig. 2(a)], whereas it decreases for the c-axis pressure (P_c) which is inferred from the low-T shift of the resistivity peak [Fig. 2(b)]. For in-plane pressure T_c does not change up to 0.04 GPa and then shows a rapid increase when P_a exceeds 0.04 GPa as plotted in Fig. 2(c). The thresholdlike behavior in T_c vs P_a is similar to that observed under hydrostatic pressures, though the threshold pressure is significantly lower in the case of uniaxial pressure. Also similar is the pressure dependence of the steplike feature at $T_d \sim 70$ K in $\rho_c(T)$ [the inset of Fig. 2(a)]. The value of T_d does not change appreciably with P_a, but the feature in $\rho_c(T)$ at T_d significantly weakens with the a-b uniaxial pressure on passing through 0.04 GPa. On the other hand, an increase of T_d with the c-axis pressure is obvious [see the inset of Fig. 2(b)], at a rate of $dT_d/dP_c \sim +24$ K/GPa, indicating that the LTT phase becomes more stable. Associated with stabilization of the LTT phase, a continuous decrease of T_c is seen in Fig. 2(b). This countercorrelation between T_c and T_d is a good demonstration of the competing SC and static stripe order.

It is instructive to compare the result with that of a Nd-free LSC (with $x = 0.15$). Using the same setup for the uniaxial pressure measurements, we observed that $dT_c/dP_a \sim +3$ K/GPa and $dT_c/dP_c \sim -9$ K/GPa [19] in overall agreement with the values estimated from the high-resolution dilatometry experiments on single crystals of LSC $dT_c/dP_a \sim +3.7$ K/GPa (a- and b-averaged value) and $dT_c/dP_c \sim -6.8$ K/GPa) [20]. This gives credit for reliability of the present uniaxial pressure measurements. Note that the signs of $dT_c/dP_{a,c}$ for LSC coincide with those for LNSC, suggesting that a similar mechanism is working in the pressure effect on T_c. Also the increase of T_d with the c-axis compression in LNSC is comparable with the increase of the LTO-HTT (high-temperature-tetragonal) phase transition temperature T'_d ($dT'_d/dP_c \sim +34$ K/GPa) for LSC [19]. The effect of in-plane compression on T'_d in LSC is much more radical. T'_d is rapidly reduced at a rate of $dT'_d/dP_a \sim 155$ K/GPa which appears to be linked to the present rapid suppression of the LTT phase under in-plane uniaxial pressure. As both LTO and LTT phases are formed by the tilt of CuO_6 octahedra, these observations strongly suggest that the c-axis compression promotes the octahedral tilt while the in-plane compression reduces the tilt angle.

Since the LTT distortions produce commensurability pinning potential for the vertical/horizontal charge stripes for $x = 1/8$, the suppression of the octahedral tilt makes the pinning potential weaker. Thus the stripes would be depinned when the tilt angle decreases below a critical value [21]. This is exactly what we observed under hydrostatic pressure, and the result of uniaxial pressure effects clearly indicate that the in-plane compression is primarily responsible for the decrease of the tilt angle and hence for the decrease in the pinning potential strength. On the other hand, the c-axis compression increases the octahedral tilt, stabilizing the static stripe phase pinned by the LTT distortions. In addition, the same trends in the pressure dependences of T_c in LSC suggest that stripe fluctuations (or dynamical stripes) might play a role. The c-axis compression may be favorable for the tilt of octahedra, which would make the stripe pinning potential stronger and slow down the stripe fluctuations, leading to the reduction of T_c. At this point, it is also possible to suppose that the increase in T_c results primarily from the c-axis expansion via the Poisson effect. It was argued that the elongation of the bond length between Cu and apex-O might favor the SC phase competing with the stripe phase [22]. However, the threshold pressure, above which T_c rapidly goes up, is by a factor of 3 lower for the in-plane pressure than that for hydrostatic pressure as seen in Figs. 1(c) and 2(c). Furthermore, in view of very similar dependences of T_c and T_d on in-plane uniaxial and hydrostatic pressure, the latter of which also compresses the crystal along the c axis, it seems more likely that the in-plane compression is of primary importance. To draw a definite conclusion, detailed investigation of the displacements of constituent atoms is necessary under hydrostatic and/or uniaxial pressures.

The promotion of superconductivity due to in-plane compression was also demonstrated for $La_{1.875}Ba_{0.125}CuO_4$ (LBC). Rapid suppression of T_d and enhancement of T_c were observed under hydrostatic pressure applied to polycrystalline samples of LBC by three groups [23–25], although the 1D to 2D crossover in R_H was not observed up to 2 GPa. Sato *et al.* reported that the 1/8 anomaly (LTT phase) of epitaxially grown LBC film with $x = 1/8$ is suppressed and T_c goes up to 40 K or higher owing to the compressive strain along the a-b plane arising from the lattice mismatch with the substrate [26].

We have demonstrated that hydrostatic pressure quite effectively controls the competition between the static stripe and high-T_c SC phases in the LNSC system. For $x = 0.12$, in which the static stripe is most stable and in turn T_c is much reduced, hydrostatic pressure of only 0.1 GPa is enough to suppress the stripes/LTT phase and to enhance T_c radically. The easiness to control the stripe implies that even the commensurability pinning of the lattice is very weak, pointing toward weak coupling between stripes and phonons. From the Hall effect it turns out that this critical change is associated with a transition from 1D to 2D charge transport. The uniaxial pressure experiment indicates that the pressure effect is caused primarily by the in-plane compression. The in-plane compression probably acts to reduce the tilt angle of CuO_6 octahedra and hence weakens the strength of stripe pinning potential leading to a pinning-depinning transition at $P \sim 0.1$ GPa.

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