Magnetic-field effects on the in-plane electrical resistivity in single-crystal $La_{2-x}Ba_xCuO_4$ and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ around $x=\frac{1}{8}$: Implication for the field-induced stripe order

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Temperature dependence of the in-plane electrical resistivity, ρ_{ab}, in various magnetic fields has been measured in the single-crystal $La_{2-x}Ba_xCuO_4$ with $x=0.08$, 0.10, 0.11 and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ with $x=0.12$. It has been found that the superconducting transition curve shows a so-called fan-shape broadening in magnetic fields for $x=0.08$, while it shifts toward the low-temperature side in parallel with increasing field for $x=0.11$ and 0.12 where the charge-spin stripe order is formed at low temperatures. As for $x=0.10$, the broadening is observed in low fields and it changes to the parallel shift in high fields above 9 T. Moreover, the normal-state value of ρ_{ab} at low temperatures markedly increases with increasing field up to 15 T. It is possible that these pronounced features of $x=0.10$ are understood in terms of the magnetic-field-induced stabilization of the stripe order suggested from the neutron-scattering measurements in the La-214 system. The ρ_{ab} in the normal state at low temperatures has been found to be proportional to $\ln(1/T)$ for $x=0.10$, 0.11, and 0.12. The $\ln(1/T)$ dependence of ρ_{ab} is robust even in the stripe-ordered state.

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I. INTRODUCTION

Magnetic fields can tune the electronic state of strongly correlated electron systems. It is well known that magnetic fields strongly affect the superconducting properties as well as the normal-state ones. For conventional superconductors, the superconducting transition curve in magnetic fields shifts to the low-temperature side in parallel with increasing field, which is attributed to the small superconducting fluctuation originating from the large superconducting coherence length. (This is called a parallel shift.) For the high-T_c cuprates, on the other hand, the superconducting transition curve shows a so-called fan-shape broadening in the underdoped regime,[1,2] which is attributed to the large superconducting fluctuation originating from the small superconducting coherence length and the quasi-two-dimensional superconductivity.

As for the magnetic-field effects on the normal-state properties, some interesting behaviors of the normal-state electrical resistivity at low temperatures below the superconducting transition temperature, T_c, have been found through the destruction of the superconductivity by the application of magnetic field. In the underdoped $La_{2-x}Sr_xCuO_4$ (LSCO), for example, the in-plane resistivity, ρ_{ab}, in the normal state exhibits an insulating behavior at low temperatures, diverging in proportion to $\ln(1/T)$, though the origin of the $\ln(1/T)$ dependence has not been clarified.[3,4] The $\ln(1/T)$ dependence has also been observed in the underdoped $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (BSLCO) below p (the hole concentration per Cu) ~ 0.12,[5] suggesting that the $\ln(1/T)$ dependence may be a common feature of ρ_{ab} in the normal state of the underdoped high-T_c cuprates at low temperatures.

Recently, magnetic-field effects on the charge-spin stripe order[6,7] have also attracted great interest. Elastic neutron-scattering measurements in magnetic fields for LSCO with $x=0.10$ (Ref. 8) under the orthorhombic mid-temperature (OMT) structure (space group: *Bmab*) have revealed that the intensity of the incommensurate magnetic peaks around (π, π) in the reciprocal lattice space increases with increasing field parallel to the c axis, suggesting the stabilization of the magnetic order. For LSCO with $x=0.12$, on the other hand, the enhancement of the incommensurate magnetic peaks is observable but small.[9] The magnetic order is considered to be almost stabilized even in zero field for $x\sim\frac{1}{8}$,[10,11] so that the development of the magnetic order by the application of magnetic field is slight. The enhancement of the incommensurate magnetic peaks has also been observed for the excess-oxygen-doped $La_2CuO_{4+\delta}$ (LCO) with the stage-4 and stage-6 structures.[12,13] For $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (LNSCO) with $x=0.15$ where the charge-spin stripe order is stabilized under the tetragonal low-temperature (TLT) structure (space group: $P4_2/ncm$), on the contrary, field effects on neither the charge nor magnetic peaks associated with the charge-spin stripe order have been observed up to 7 T.[14] These results suggest that a sort of spin stripe order in the OMT phase of LSCO and in LCO is stabilized by the application of magnetic field, while the charge-spin stripe order in the TLT phase of LNSCO is almost never affected.

In this paper, with the aim to clarify the relation between the superconducting and normal-state properties and the formation of the stripe order, we have performed ρ_{ab} measurements in magnetic fields up to 15 T for the single-crystal $La_{2-x}Ba_xCuO_4$ (LBCO) with $x=0.08$, 0.10, 0.11 and LNSCO with $x=0.12$. As shown in Fig. 1, it is noted that both LNSCO with $x=0.12$ and LBCO with $x=0.11$ are located in the regime where the superconductivity is suppressed in the neighborhood of $p=x=\frac{1}{8}$, while LBCO with $x=0.08$ is lo-

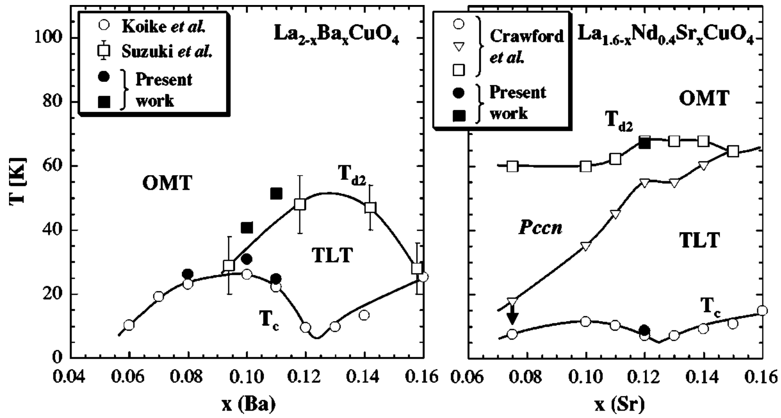

FIG. 1. (Left) Phase diagram of $La_{2-x}Ba_xCuO_4$. Open circles represent T_c, defined as the midpoint temperature in the resistive superconducting transition (Ref. 15). Open squares represent the structural phase-transition temperature between the OMT and TLT phases, T_{d2} (Ref. 16). (Right) Phase diagram of $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (Ref. 17). Open circles represent T_c. Open squares represent the structural phase-transition temperature between the OMT and TLT/*Pccn* phases, T_{d2}. Open triangles represent the temperature between the *Pccn* and TLT phases. Closed circles and squares in both diagrams represent the present T_c and T_{d2} estimated from the ρ_{ab} measurements, respectively.

cated outside this regime. LBCO with $x=0.10$ is just at the boundary between the inside and outside of this regime. In the elastic neutron-scattering measurements of LBCO (Ref. 18) and LNSCO (Refs. 6, 7), the incommensurate elastic charge and magnetic peaks associated with the stripe order have been observed for $x=0.10$ and 0.12 below the structural phase-transition temperature between the OMT and TLT/*Pccn* phases, T_{d2}, in zero field, but not for $x=0.08$. These mean that the static charge-spin stripe order is formed at low temperatures below T_{d2} for $x=0.10$, 0.11, and 0.12 even in zero field. Moreover, it has been found that the intensity of the elastic charge peaks is weaker in $x=0.10$ than in $x\sim\frac{1}{8}$ of LBCO,[18,19] suggestive of a less-stabilized static charge order in $x=0.10$. For $x=0.08$, on the other hand, the stripe order is not stabilized even at low temperatures.

II. EXPERIMENTS

Single crystals of LBCO with $x=0.08$, 0.10, 0.11 and LNSCO with $x=0.12$ were grown by the traveling-solvent floating-zone method under flowing O_2 gas of 4 bar. The detailed procedures are described elsewhere.[20] Ba and Sr contents of each crystal were analyzed by the inductively-coupled-plasma atomic-emission-spectrometry (ICP-AES) measurements. The ρ_{ab} was measured by the standard dc four-probe method on field cooling in magnetic fields parallel to the c axis up to 15 T.

III. RESULTS

Figure 2 displays the temperature dependence of ρ_{ab} in various magnetic fields for LBCO with $x=0.08$, 0.10, 0.11 and LNSCO with $x=0.12$. For $x=0.10$, 0.11, and 0.12, a jump in ρ_{ab} is observed at $T_{d2}\sim41$ K, ~51 K, and ~67 K with decreasing temperature, respectively. For $x=0.08$, no jump is observed, suggesting that no structural transition to the TLT phase occurs and that the OMT phase remains at least down to the lowest measured temperature of 1.5 K.[18]

Focusing the attention on the superconducting transition curve, the broadening is observed with increasing field for $x=0.08$, as usually observed in the underdoped high-T_c cuprates. For $x=0.11$, on the other hand, it is found that the superconducting transition curve shifts to the low-temperature side in parallel with increasing field.[21] To be more visible, contour maps of ρ_{ab} in the H vs T plane are shown in Fig. 3 for LBCO with $x=0.08$, 0.10, and 0.11. In each x, the region where the color starts to change from that at high temperatures of ~60 K with decreasing temperature roughly corresponds to the onset region of the superconducting transition. For $x=0.08$, it is found that the relatively sharp transition of ρ_{ab} around T_c in zero field is broadened with increasing field. For $x=0.11$, on the contrary, the transition of ρ_{ab} around T_c remains sharp even in magnetic fields. The parallel shift of ρ_{ab} is also observed for $x=0.12$ in LNSCO as shown in Fig. 2. These suggest an intimate relation between the parallel shift and the suppression of superconductivity around $p=\frac{1}{8}$ or the formation of the charge-spin stripe order.

A remarkable feature is for $x=0.10$ that the superconducting transition curve shows the broadening in low fields, while it changes to the parallel shift in high fields above 9 T. In Fig. 3, it is found that the broad transition of ρ_{ab} around T_c below 9 T changes to the sharp one above 9 T for $x=0.10$. This dramatic change indicates that the application of magnetic field causes a crossover from the usual state of the underdoped high-T_c cuprates to the peculiar state around $p=\frac{1}{8}$.

Another remarkable feature observed for $x=0.10$ is that the normal-state-like behavior of ρ_{ab}, characterized by the almost linear T dependence, is observed between T_{d2} and the onset temperature of superconductivity, T_c^{onset}, of ~15 K at 9 T and that ρ_{ab} between T_{d2} and T_c^{onset} increases with increasing field above 9 T and finally exhibits an insulating behavior for $H\geqslant13$ T. For $x=0.11$ and 0.12, on the other hand, the increase of ρ_{ab} between T_{d2} and T_c^{onset} with increasing field is negligibly small up to 15 T, compared with that for $x=0.10$. To summarize, LBCO with $x=0.08$ is a typical

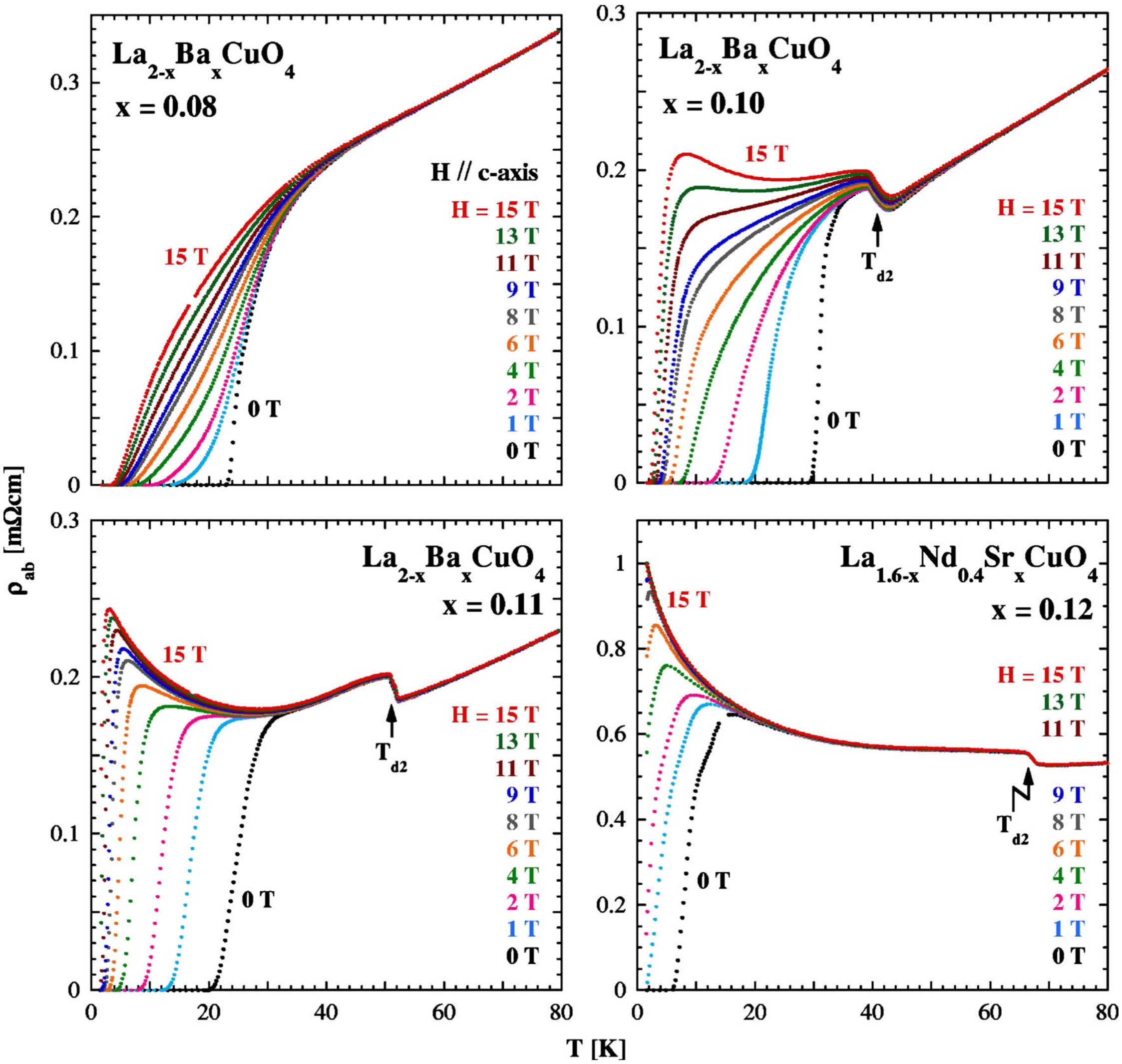

FIG. 2. (Color online) Temperature dependence of the in-plane electrical resistivity, ρ_{ab}, in various magnetic fields parallel to the c axis for $La_{2-x}Ba_xCuO_4$ with $x=0.08$, 0.10, 0.11 and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ with $x=0.12$. The temperature where a jump of ρ_{ab} occurs is in correspondence to the structural phase-transition temperature between the OMT and TLT/*Pccn* phases, T_{d2}.

underdoped sample characterized by the broadening of the superconducting transition curve in magnetic fields. Both LBCO with $x=0.11$ and LNSCO with $x=0.12$ are peculiar samples around $p=\frac{1}{8}$ characterized by the parallel shift of the superconducting transition curve in magnetic fields. LBCO with $x=0.10$ is a rather unique sample that shows the broadening in low fields and the parallel shift in high fields above 9 T, and whose ρ_{ab} in the normal state below T_{d2} markedly increases with increasing field up to 15 T.

IV. DISCUSSION

First, we discuss the intimate relation between the superconducting transition curve and the stripe order. It is well known that the broadening of the superconducting transition curve observed for $x=0.08$ is characteristic of the underdoped high-T_c cuprates with large superconducting fluctuation.[1,2] On the other hand, the parallel shift of the superconducting transition curve is observed for $x=0.11$ and 0.12 and for $x=0.10$ above 9 T. The parallel shift has also been observed in LNSCO with $x=0.15$ (Ref. 14) and LSCO with $x=0.12$ (Ref. 22) where the static stripe order of charges and/or spins is formed at low temperatures. These suggest that both the superconductivity with small superconducting fluctuation and the static stripe order are realized in one sample. Here, it is an important issue whether the superconducting region and the static stripe-ordered one coexist microscopically or are separated macroscopically. From the neutron-scattering measurements in $La_{1.875}Ba_{0.125-x}Sr_xCuO_4$, the static stripe order has been suggested to compete with the superconductivity.[23] Moreover, from the muon-spin-relaxation measurements in $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ around $x=\frac{1}{8}$, it has been suggested that the superconductivity is destroyed in a region where frequencies of the dynamical stripe fluctuations are lower than $\sim10^{11}$ Hz.[24] Therefore, the superconducting region and the static stripe-ordered one are probably separated macroscopically.

The reason why the superconductivity with small superconducting fluctuation is realized in a sample with the static

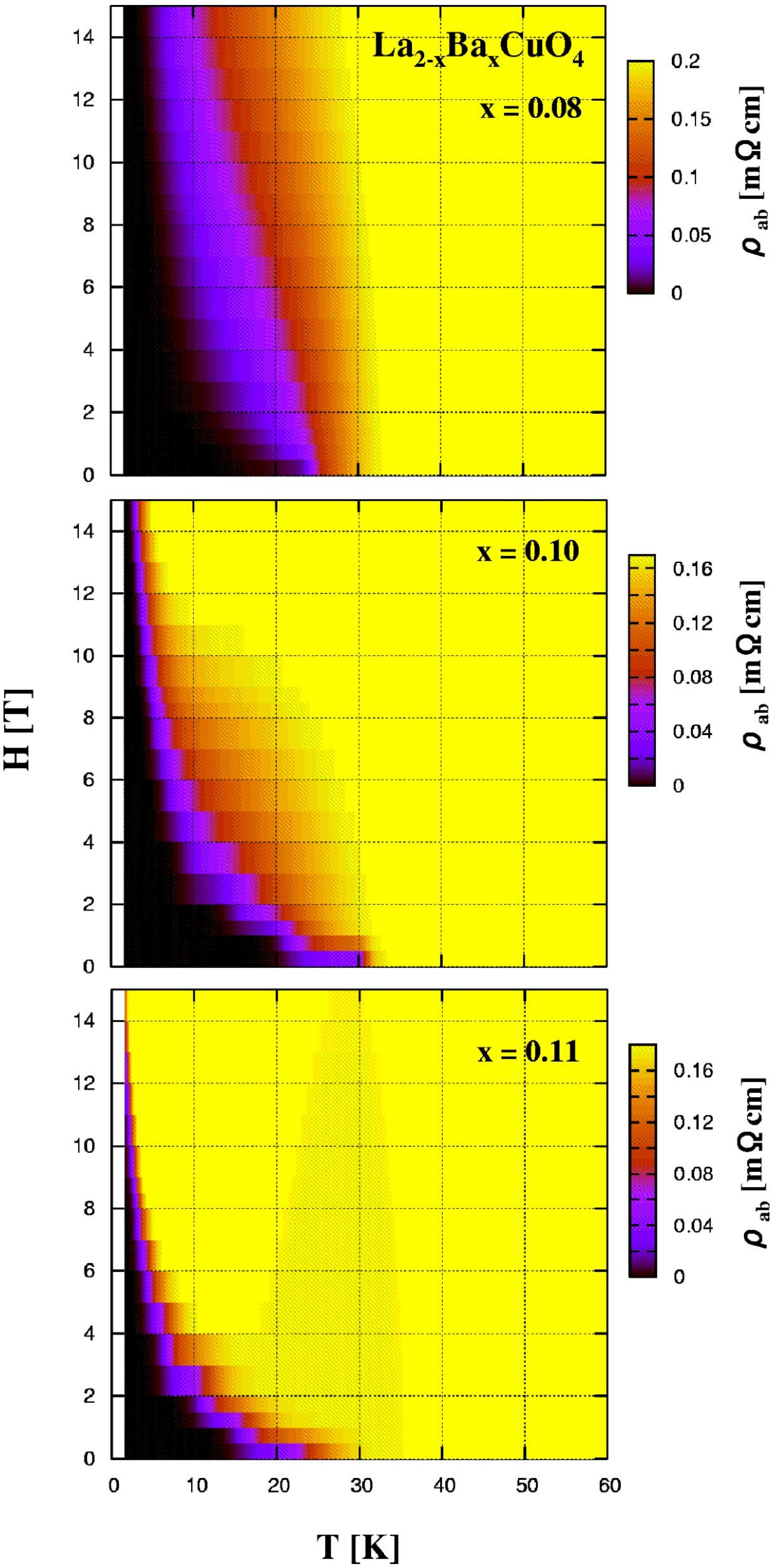

FIG. 3. (Color online) Contour maps of ρ_{ab} in the H vs T plane for $La_{2-x}Ba_xCuO_4$ with $x=0.08$, 0.10, and 0.11.

stripe-ordered region is still an open question. A possible origin is that the out-of-plane superconducting coherence length, ξ_c, might be relatively large under the influence of the correlation of the static stripe order along the c axis,[7,25] leading to the three-dimensional superconductivity with small superconducting fluctuation.

Next, we discuss the relation between the change of the normal-state behavior of ρ_{ab} in magnetic fields and the field-induced stripe order. Considering the results of the elastic neutron-scattering measurements[6,7,18,19] mentioned in Sec. I, the negligibly small increase of ρ_{ab} below T_{d2} with increasing field for $x=0.11$ and 0.12 seems to indicate that the stripe order is nearly perfectly stabilized in zero field and is insensitive to the applied field.[14] As for $x=0.10$, the marked increase of ρ_{ab} below T_{d2} with increasing field reminds us some possible origins. The first is the normal-state magnetoresistance. However, this is not applicable, because the normal-state magnetoresistance is usually as small as an order of 1 % at 15 T, as in the case of $x=0.11$ and 0.12. The second is the suppression of the superconducting fluctuation by the applied field. The positive magnetoresistance appears even at temperatures just below T_{d2} far from T_c^{onset} in high fields. On the other hand, reports on the Nernst effect in LSCO have suggested that the vortex state survives even at higher temperatures far above T_c, meaning that the superconducting fluctuation exists even at high temperatures.[26,27] Therefore, this possible origin cannot be excluded and further measurements are needed to conclude. Nevertheless, it appears that this is not a candidate, because the large positive magnetoresistance is observed only for $x=0.10$ and not for $x=0.11$ or 0.12. The third is enhancement of the localization of holes induced by the applied field. The localization behavior of ρ_{ab} becomes marked with increasing field and appears to approach the behavior of LNSCO with $x=0.12$ where the stripe order is perfectly stabilized. In the long run, the most probable origin is that the charge-spin stripe order is stabilized by the applied field in $x=0.10$. This may be the first experimental evidence, to our knowledge, of the *charge* stripe order stabilized in magnetic fields. To be more conclusive, the neutron scattering measurements in magnetic fields are under way.

Finally, we discuss the temperature dependence of ρ_{ab} below T_{d2}. So far, it has been clarified in the underdoped LSCO and BSLCO (Refs. 3–5) that ρ_{ab} in the normal state shows the $\ln(1/T)$ dependence at low temperatures in magnetic fields, suggesting that the $\ln(1/T)$ dependence is a common feature of the underdoped high-T_c cuprates. To check this suggestion, ρ_{ab}'s of LBCO with $x=0.10$, 0.11 and LNSCO with $x=0.12$ at 15 T are plotted versus $\ln T$, as shown in Fig. 4. Below ~20 K, it is found that ρ_{ab} in the normal state is proportional to $\ln(1/T)$ in each x, though ρ_{ab} deviates downward from $\ln(1/T)$ at low temperatures because of the superconducting transition for $x=0.10$ and 0.11. The small deviation below 3 K for $x=0.12$ is irrelevant to the superconducting transition, because ρ_{ab} is independent of the field strength for $H \geqslant 11$ T, as seen in Fig. 2. The slope of the $\ln(1/T)$ dependence is found to increase with increasing x, indicating that the localization of holes becomes strong with increasing x toward $x=\frac{1}{8}$ at 15 T. The $\ln(1/T)$ dependence is known to be characteristic of the weak localization and the electron-electron interaction in the two-dimensional Anderson-localized state where the in-plane electrical conductivity, σ_{ab}, actually changes in proportion to $\ln(1/T)$ even in magnetic fields.[28] For $x=0.10$, 0.11, and 0.12, however, σ_{ab} does not show the $\ln(1/T)$ dependence below T_{d2}, as in the case of the underdoped LSCO.[3,4] Although the true origin of the $\ln(1/T)$ dependence of ρ_{ab} is not clear, the localization of holes with the $\ln(1/T)$ dependence observed widely in the underdoped high-T_c cuprates is robust even in the stripe-ordered state of LBCO and LNSCO.[29]

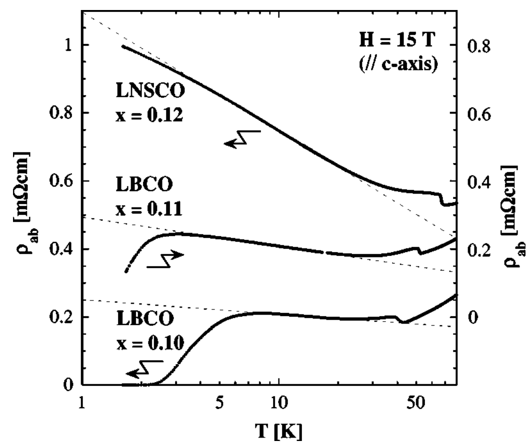

FIG. 4. Plot of ρ_{ab} vs $\ln T$ at 15 T for $La_{2-x}Ba_xCuO_4$ (LBCO) with $x=0.10$, 0.11 and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (LNSCO) with $x=0.12$.

V. SUMMARY

It has been found that the superconducting transition curve shows the parallel shift by the application of magnetic field in LBCO with $x=0.11$ and LNSCO with $x=0.12$ where the charge-spin stripe order is formed at low temperatures. These suggest that both the superconductivity with small superconducting fluctuation and the static stripe order are realized in one sample for $x=0.11$ and 0.12. For LBCO with $x=0.10$, the broadening in low fields changes to the parallel shift in high fields above 9 T. Moreover, ρ_{ab} in the normal state below T_{d2} increases with increasing field up to 15 T. It is possible that these pronounced features of $x=0.10$ are understood in terms of the field-induced stabilization of the *charge* stripe order. The ρ_{ab} in the normal state at low temperatures has been found to be proportional to $\ln(1/T)$ for $x=0.10$, 0.11, and 0.12, suggesting the localization of holes with the $\ln(1/T)$ dependence of ρ_{ab} which is robust even in the stripe-ordered state of LBCO and LNSCO.

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