Heat transport of $La_{2-y}Eu_yCuO_4$ and $La_{1.88-y}Eu_ySr_{0.12}CuO_4$ single crystals

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To study the rare-earth doping effect on the phonon heat transport of La-based cuprates and shed light on the mechanism of phonon scattering, both ab-plane and c-axis thermal conductivities (κ_{ab} and κ_c) are measured for $La_{2-y}Eu_yCuO_4$ ($y=0$, 0.02 and 0.2) and $La_{1.88-y}Eu_ySr_{0.12}CuO_4$ ($y=0$ and 0.2) single crystals. It is found that the phonon peak (at 20–25 K) in $\kappa_{ab}(T)$ of $La_{2-y}Eu_yCuO_4$ shows an anomalous Eu-doping dependence: it completely disappears for $y=0.02$, which is discussed to be due to the local lattice distortions around Eu dopants, and reappears for $y=0.2$ with much smaller peak magnitude compared to $y=0$ sample. In contrast to the strong suppression of the phonon peak in Eu-doped La_2CuO_4, Eu-doping to $La_{1.88}Sr_{0.12}CuO_4$ enhances the low-T phonon heat transport that results in the reappearance of the phonon peak in this charge-carrier-doped system. The data clearly show that the establishment of static stripe phase rather than the structural change is responsible for the reappearance of phonon peak.

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I. INTRODUCTION

In $La_{2-x}Sr_xCuO_4$ (LSCO) related compounds, the high-temperature structure is tetragonal (HTT, space group $I4/mmm$) and there are three different low-temperature phases:[1,2] the LTO (low-temperature orthorhombic, space group $Bmab$) phase in LSCO, the LTO2 (low-temperature orthorhombic 2, space group $Pccn$) phase in rare-earth (R) doped $La_{2-x-y}R_ySr_xCuO_4$, and LTT (low-temperature tetragonal, space group $P4_2/ncm$) phase in $La_{2-x-y}R_ySr_xCuO_4$ with larger x. These low-temperature structures are classified[1] by the tilts of CuO_6 octahedra around [110] and $[1\bar{1}0]$ axes of the HTT phase and have pronounced influence on the physical properties. For example, it has recently been realized that the holes in the high-T_c cuprates mesoscopically segregate into quasi-one-dimensional antiphase domain boundaries between antiferromagnetically ordered Cu spin regions, which is the so-called stripe phase;[3–16] the static stripe order of charges and spins is only established in R (Nd,Eu)-doped LSCO,[3,9,17–19] where the stripes are believed to be pinned by the particular tilting of CuO_6 octahedra in the LTT phase.[3]

It is known that the antiferromagnetic (AF) insulating compound La_2CuO_4 (LCO), which has LTO phase, shows predominant phonon heat transport at low temperatures, which is manifested in a large phonon peak at 20–25 K in the temperature dependence of both ab-plane and c-axis thermal conductivities (κ_{ab} and κ_c);[20,21] such phonon peak was found to be completely suppressed in LSCO with $x=0.10$–0.20.[20] Interestingly, it was found that in R-doped LSCO, such as $La_{1.28}Nd_{0.6}Sr_{0.12}CuO_4$, the low-$T$ thermal conductivity is much enhanced in the nonsuperconducting LTT phase, compared to that in LSCO with the same Sr content.[22] This cannot happen if the defect scattering and electron scattering of phonons are the only source of the phonon peak suppression in LSCO. Alternatively, it was proposed that the strong suppression of phonon heat transport in LSCO is due to the strong phonon scattering by the structural distortion associated with the dynamical stripes, while R-doping leads to the formation of static stripes that significantly reduces the phonon scattering.[22] However, this supposition would be too straightforward, because the low-T structure phases are LTO and LTT in LSCO and R-doped LSCO, respectively, which possess different phonon spectra and phonon scattering. In fact, it has already been reported that the structural symmetry does affect the phonon properties; for example, the sound velocities in the three structures are known to be $v_s(\mathrm{LTT})>v_s(\mathrm{LTO2})>v_s(\mathrm{LTO})$,[23] which implies that the phononic thermal conductivity is likely the largest in the LTT phase and the smallest in the LTO phase. Apparently, it is not a solid conclusion that the reappearance of phonon peak in R-doped LSCO is due to the formation of static stripes, until evidence showing a direct relationship between the low-T phonon heat transport and the static charge stripes (rather than the structural transition) is obtained. Another question, apart from the structural phase transition, is how the R dopants themselves affect the phonon heat transport. A previous study on the Nd-doped LCO (without charge doping) has shown that the phonon transport is somehow suppressed by Nd-doping;[24] however, no clear R-doping dependence of the heat conductivity was reported, probably because only polycrystalline samples were used in that study. It is, therefore, desirable to clarify the role of R-doping in the phonon heat transport by studying both R-doped LCO and R-doped LSCO single crystals.

To reduce the possible effect of magnetic moments of rare-earth ions on the heat transport behavior, we select Eu ion as the dopant, which has the smallest magnetic moment among rare-earth ions (atomic number 57–71), except for La and Lu. In this paper, we report our study of the Eu doping effect on the phonon heat transport in two single-crystal systems: $La_{2-y}Eu_yCuO_4$ ($y=0$, 0.02, and 0.2) and $La_{1.88-y}Eu_ySr_{0.12}CuO_4$ ($y=0$ and 0.2), which have LTO2 and LTT phases for $y=0.2$, respectively, at low temperature. It is found that for LCO slight Eu-doping ($y=0.02$) induces anomalous wipeout of the phonon peak in κ_{ab}, which is due to the local structural distortions induced by the local LTO2 regions around Eu ions in the LTO phase, while further increase of Eu content ($y=0.2$) recovers the phonon peak, although the peak magnitude is much smaller than that of undoped LCO. These results clearly show that rare-earth doping strongly suppress the phonon heat transport in LCO. On the contrary, the Eu doping in LSCO enhances the low-T phonon transport, which, based on the new features found in our single crystals, we discuss to be most likely related to the formation of static stripes.

II. EXPERIMENTS

The single crystals of $La_{2-y}Eu_yCuO_4$ and $La_{1.88-y}Eu_ySr_{0.12}CuO_4$ are grown by the traveling-solvent floating-zone (TSFZ) technique and carefully annealed.[25] After the crystallographic axes are determined by using the x-ray Laue analysis, the crystals are cut into rectangular thin platelets with the typical sizes of $2.5\times0.5\times0.15$ mm^3, where the c axis is perpendicular or parallel to the platelet with an accuracy of 1°. $La_{2-y}Eu_yCuO_4$ samples are annealed in flowing pure He gas to remove the excess oxygen. On the other hand, $La_{1.88-y}Eu_ySr_{0.12}CuO_4$ samples are annealed at 850 °C for 48 h in air, followed by rapid quenching to room temperature, to remove the oxygen defects.

The thermal conductivity κ is measured using a conventional steady-state technique at 2–150 K and a modified steady-state technique at 150–300 K.[21] The temperature difference ΔT on the sample is measured by a differential Chromel-Constantan thermocouple, which is glued to the sample using GE7031 varnish. The ΔT varies between 0.5% and 2% of the sample temperature. To improve the accuracy of the measurement at low temperatures, κ is also measured with "one heater, two thermometer" method from 2 to 20 K by using a chip heater and two Cernox chip sensors.[26,27] The errors in the thermal conductivity data are smaller than 10%, which is mainly caused by the uncertainties in the geometrical factors. Magnetization measurements are carried out using a Quantum Design SQUID magnetometer.

III. RESULTS AND DISCUSSION

A. Thermal conductivity of $La_{2-y}Eu_yCuO_4$

Figure 1 shows the temperature dependences of the thermal conductivity measured along the ab plane and the c axis in pure LCO and Eu-doped LCO single crystals. The undoped La_2CuO_4 sample, as has already been discussed in a previous paper,[21] shows a sharp phonon peak at low temperature [$\sim$25 K in $\kappa_{ab}(T)$ and $\sim$20 K in $\kappa_c(T)$] and a broad magnon peak in $\kappa_{ab}(T)$ at high temperature ($\sim$270 K).

Upon Eu doping, there are drastic changes in both κ_{ab} and κ_c. Let us first discuss the changes of the high-T magnon peak in $\kappa_{ab}(T)$. This peak is suppressed gradually upon Eu doping, which is directly related to the suppression of the Néel transition temperature by Eu doping. The detailed magnetic behaviors of these samples are shown in the following subsection.

The phonon peak at low temperatures shows an anomalous change with Eu doping. For $La_{1.98}Eu_{0.02}CuO_4$, with only 1% Eu substitution, the phonon peak in $\kappa_{ab}(T)$ is completely suppressed although the magnon peak shows only slight decrease. One natural phonon scattering process is caused by the point defects associated with dopants. However, it is found that the suppression of the phonon peak is much

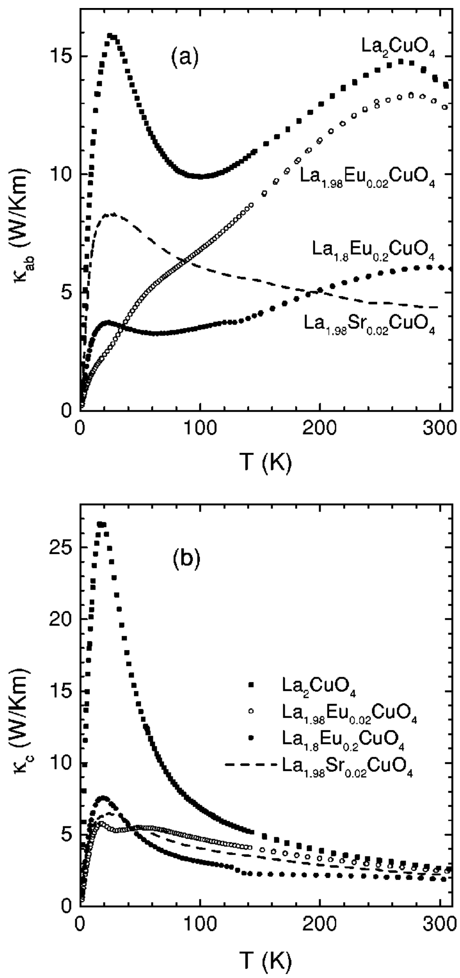

FIG. 1. Thermal conductivity of $La_{2-y}Eu_yCuO_4$ ($y=0$, 0.02, and 0.2) single crystals along (a) the ab plane and (b) the c axis. The data of $La_{1.98}Sr_{0.02}CuO_4$ single crystal are also shown for comparison.

weaker in $La_{1.98}Sr_{0.02}CuO_4$ with the same amount of dopants, as shown in Fig. 1(a), which suggests that the impurity atoms themselves are not the main source of such strong phonon scattering in $La_{1.98}Eu_{0.02}CuO_4$. Another possible mechanism may be the magnetic scattering of phonons since Eu^{3+} ions have magnetic moments and may disturb phonons by magnetoelastic coupling.[28,29] If this is the case, some magnetic field dependence of thermal conductivity is expected (at least in the temperature region near the phonon peak where the phonon transport is most strongly suppressed with Eu doping). Figure 2 shows the field dependence of κ_{ab} measured with magnetic field parallel to the c axis or to the ab plane for this $La_{1.98}Eu_{0.02}CuO_4$ single crystal. In both cases, there is no substantial magnetic-field dependence up to 6 T at 12.5 K and 18.5 K. Therefore, magnetic origin for the strong phonon scattering is not likely. The last possible cause of the strong suppression of the phonon peak is the phonon scattering by the structural distortions introduced by Eu doping. It is known that a certain degree of Eu doping in LCO is necessary to induce the structural phase transition from LTO to LTO2.[30–32] When the doping level is too small to induce the macroscopic structural transition, it is most likely that the

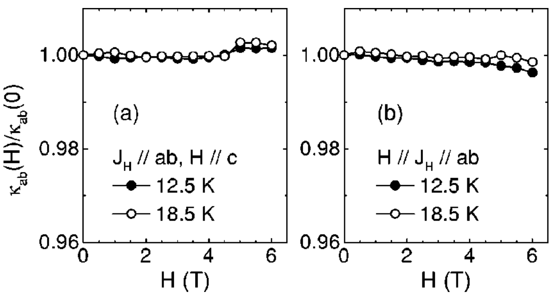

FIG. 2. Magnetic field dependence of in-plane thermal conductivity of $La_{1.98}Eu_{0.02}CuO_4$ single crystal measured with magnetic field parallel to (a) the c axis and (b) the ab plane, respectively.

LTO2-like tilts of the CuO_6 octahedra exist locally around Eu^{3+} ions in the background of LTO phase, which results in very strong lattice distortions that significantly scatter phonons. It should be noted that, since Sr doping can never induce phase transition from LTO to LTO2/LTT, the lattice distortions in $La_{1.98}Sr_{0.02}CuO_4$ are expected to be much weaker.

With increasing Eu concentration, the local LTO2 regions around Eu^{3+} ions are expected to percolate at low temperature and the macroscopic structural transition takes place. The cooperative tilt of CuO_6 octahedra in LTO2 phase would weaken the lattice distortions and the phonon scattering, which is actually observed in $La_{1.8}Eu_{0.2}CuO_4$. As shown in Fig. 1(a), the phonon peak, although still very weak, reappears in $La_{1.8}Eu_{0.2}CuO_4$.

The Eu-doping dependence of κ_c shows that the effect of lattice distortion related to the LTO2 phase on the phonon transport is weaker in the c axis than in the ab plane. One can see in Fig. 1(b) that the phonon peak still exists in κ_c of $La_{1.98}Eu_{0.02}CuO_4$, and the peak height is comparable to that in $La_{1.98}Sr_{0.02}CuO_4$ (where the disordering of static spin stripes in the c axis causes rather strong phonon scattering[21]). However, the temperature dependence of κ_c in $La_{1.98}Eu_{0.02}CuO_4$ is too complicated (because of a double peak feature) to extract any detailed information of the phonon transport. Nevertheless, the c-axis phonon peak is larger in $La_{1.8}Eu_{0.2}CuO_4$ than in $La_{1.98}Eu_{0.02}CuO_4$, similar to that in the ab plane.

The above results show that in lightly Eu-doped LCO, the structural distortions associated with the local LTO2 regions strongly scatter ab-plane phonons. Such structural distortions and phonon scattering become weaker when the Eu concentration is large enough to stabilize the macroscopic LTO2 phase at low temperatures. However, compared to the pure LCO, the phonon peak is strongly suppressed even in $La_{1.8}Eu_{0.2}CuO_4$ which has global LTO2 phase. There are two possible reasons for such difference. First, it may come from the difference in phonon spectrum between LTO and LTO2 phases, which is, however, not very likely; as can be seen in Fig. 1, both κ_{ab} and κ_c of $La_{1.8}Eu_{0.2}CuO_4$ show a steplike increase at ~ 130 K when the structure changes from LTO to LTO2 phase, which means the LTO2 phase essentially has better phonon heat transport than the LTO phase. Another, more likely reason is simply the impurity scattering by Eu dopants.

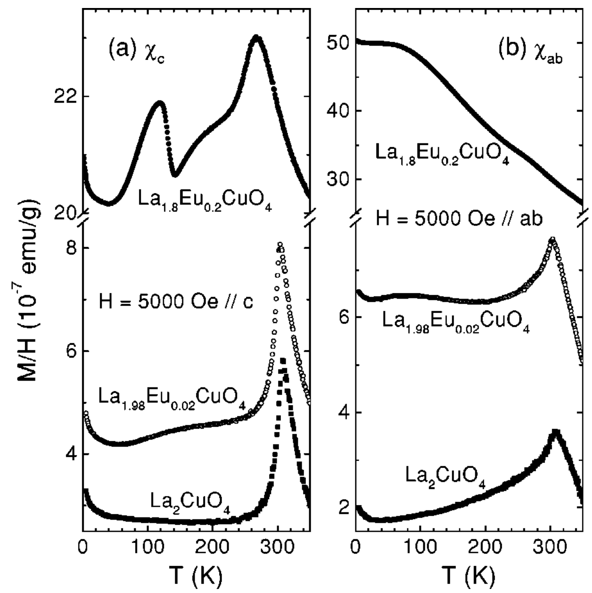

FIG. 3. Magnetic susceptibility of $La_{2-y}Eu_yCuO_4$ single crystals measured in 5000 Oe field applied along (a) the c axis and (b) the ab plane.

B. Magnetic properties of $La_{2-y}Eu_yCuO_4$

It is well known that the magnetic properties of La_2CuO_4 are determined by the Cu spins. At high temperatures, LCO is essentially a two-dimensional Heisenberg antiferromagnet and a weak interlayer coupling gives rise to the three-dimensional long-range Néel order.[33,34] In the LTO phase of LCO, the spin easy axis is the b axis and all the spins are weakly canted along the c axis. Such canted moments depend on the tilting of CuO_6 octahedra; they become weaker in the LTO2 phase and disappear in the LTT phase.[31] Thus, it is helpful to study the magnetic properties for understanding the Eu-doping effect on local structure. Figure 3 shows the magnetic susceptibility data of Eu-doped LCO single crystals measured with 5000 Oe field applied along the c axis or the ab plane. The pure LCO sample shows a sharp Néel transition in χ_c and a much broader peak in χ_{ab} at $T_N = 307$ K, which originates from the AF ordering of Cu^{2+} canted moments.[35–37]

Eu doping induces pronounced changes in the magnetic properties of $La_{1.8}Eu_{0.2}CuO_4$, as shown in Fig. 3. First, both χ_c and χ_{ab} data are shifted up significantly. This additional signals apparently come from the Van Vleck contribution of Eu^{3+} ions, which is weakly T dependent in χ_c and noticeably T-dependent in χ_{ab}, respectively. (Note that the Van Vleck term, although is independent of temperature in usual cases, can be T-dependent when the energy difference between the ground state and the excited orbital state is smaller than k_BT, as shown for Eu_2CuO_4.[38]) Second, a clear Néel transition shows up in χ_c with lower T_N (268 K) compared to undoped LCO, while the corresponding peak is almost smeared out in χ_{ab} (only a slight hump at T_N) because of the strong T dependence of χ_{ab}. Third, another transition appears in χ_c at the structural transition temperature, which is due to the suppression of canted moments in the LTO2 phase and the reduction of the interlayer magnetic coupling.[31] It is not clear whether there is a corresponding transition in χ_{ab} because of its strong T dependence. The details of the magnetic structure in $La_{1.8}Eu_{0.2}CuO_4$ are thoroughly discussed elsewhere.[31] It should be pointed out that the susceptibility data of the present single crystal are different from the previous report, which used polycrystalline samples and claimed that $La_{1.8}Eu_{0.2}CuO_4$ has the LTT structure.[39]

For Eu-1% doping, the susceptibility data show moderate changes. First, the enhancement of both χ_c and χ_{ab} are much smaller than those in $La_{1.8}Eu_{0.2}CuO_4$. Second, the Néel transition is only slightly shifted to a lower temperature ($T_N = 304$ K). Thus, the high temperature magnetic properties do not show any drastic change upon Eu doping, which is understandable because the structural changes associated with Eu doping only happen at low temperatures. This is also consistent with the weak change of the high-T magnon peak in κ_{ab}. (In contrast, the magnon peak disappears in $La_{1.98}Sr_{0.02}CuO_4$ (Fig. 1), in which the Néel transition also disappears.[21,34]) Third, there is no second transition in χ_c at ~ 130 K, because there is no structural phase transition in this lightly-doped sample. However, χ_c decreases slowly with deceasing temperature from ~ 150 K to 50 K and χ_{ab} shows a weak hump at the same temperature region. This is in correspondence with our picture that slight Eu-doping induces local LTO2 regions in the LTO background, although no macroscopic structural transition occurs.

C. Phonon peak in $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$

While Eu doping significantly suppresses the phonon peak in the non-carrier-doped LCO, it shows quite different effects on the phonon heat transport of LSCO. The $\kappa_{ab}(T)$ and $\kappa_c(T)$ data for $La_{1.88}Sr_{0.12}CuO_4$ and $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ single crystals are shown in Fig. 4, in which the data for $La_{1.8}Eu_{0.2}CuO_4$ are also included for comparison. Since there are certain amount of charge carriers doped by Sr, we should separate the electronic contribution from the total thermal conductivity before discussing the mechanism for the phonon heat transport.

The electronic thermal conductivity κ_e and the electrical resistivity ρ are related by $\kappa_e = LT/\rho$, where L is called the Lorenz number. In simple metals, L is usually constant at high-T and low-T (the Wiedemann-Franz law) and is given by the Sommerfeld value 2.44×10^{-8} WΩ/K^2. When the electron-electron correlation becomes strong, L becomes smaller. For $YBa_2Cu_3O_{7-\delta}$, L has been estimated to be $1.2-2.0\times10^{-8}$ WΩ/K^2 near T_c by Hirschfeld and Putikka,[40] while Takenaka *et al.*[41] estimated L to be $2.4-3.3\times10^{-8}$ WΩ/K^2 above T_c. So there is still no consensus value of L for cuprates. Here, we roughly estimate κ_e of our crystals by using the Sommerfeld value. The in-plane resistivity ρ_{ab} of $La_{1.88}Sr_{0.12}CuO_4$ and $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ are measured using a standard ac four-probe method and shown in the inset of Fig. 5. We note that the zero resistance at 5 K in $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ is a filamentary superconducting effect, since the dc susceptibility measurement does not show any bulk superconductivity in this sample. The main panel of Fig. 5 shows the estimated in-plane phononic thermal conductivity $\kappa_{ph,ab}$ ($=\kappa_{ab}-\kappa_{e,ab}$). It can be seen that the main

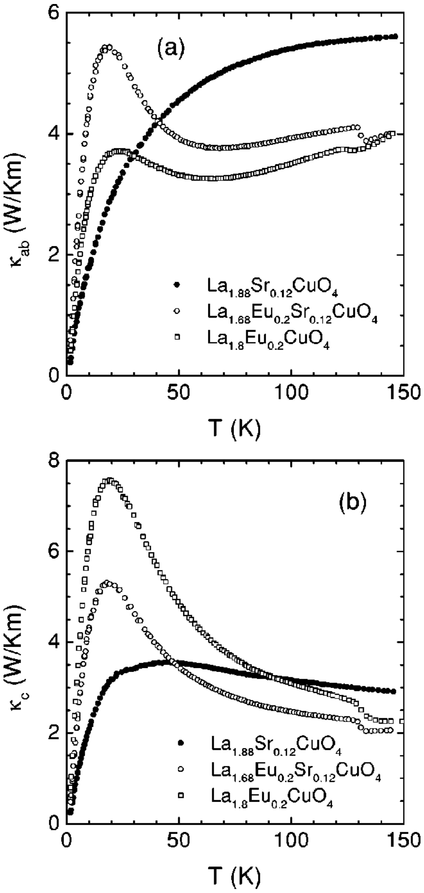

FIG. 4. Low-temperature thermal conductivity of $La_{1.88}Sr_{0.12}CuO_4$ and $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ single crystals. The data for $La_{1.8}Eu_{0.2}CuO_4$ are also shown for comparison. The steplike feature at ~ 130 K is due to the LTO→LTT and LTO→LTO2 structural transition for $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ and $La_{1.8}Eu_{0.2}CuO_4$, respectively.

contribution to thermal conductivity is phononic in these samples. For the c-axis heat transport, the electronic contribution is negligibly small because of the 2–3 orders of magnitude larger electrical resistivity in the c axis compared to ρ_{ab}.[42,43] The experimental data for κ_c is nearly pure phonon conductivity.

Clearly, the phonon heat transport is strongly damped in $La_{1.88}Sr_{0.12}CuO_4$, which shows complete disappearance of the phonon peak in κ_{ab} and a weak hump in κ_c. The strong phonon scattering can be related to the Sr dopants acted as impurities, the charge carriers, and the structural distortions associated with dynamical stripes. Eu doping in this LSCO system significantly increases the low-T phononic thermal conductivity; clear phonon peak reappears in both κ_{ab} and κ_c. Similar behavior in R-doped LSCO was first attributed by Baberski *et al.*[22] to the weakening of phonon scattering in the static stripe phase. However, their data were collected on polycrystalline samples and did not display quantitative difference between LSCO and R-doped LSCO. Here the data on single crystals show convincing evidence for the importance of static stripes on the phonon transport. In this Eu-doped LSCO, LTO→LTT structural transition takes place at ~ 130 K (Refs. 18 and 30) and results in a steplike increase

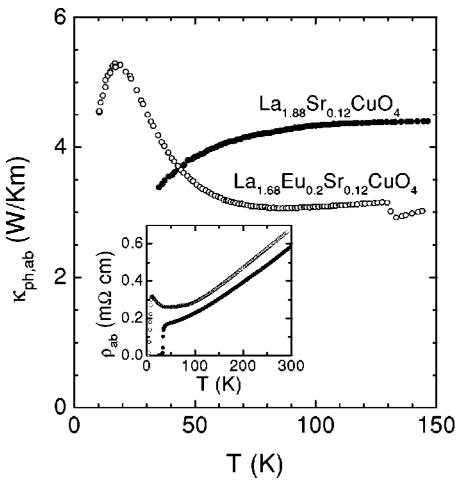

FIG. 5. Comparison of the in-plane phononic thermal conductivity $\kappa_{ph,ab}$ of $La_{1.88}Sr_{0.12}CuO_4$ single crystal to that of $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ crystal; the electronic thermal conductivity $\kappa_{e,ab}$ is estimated from the in-plane resistivity data by the Wiedemann-Franz law and $\kappa_{ph,ab} = \kappa_{ab} - \kappa_{e,ab}$. Inset: in-plane resistivity data for $La_{1.88}Sr_{0.12}CuO_4$ (solid circles) and $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ (open circles).

of the phononic thermal conductivity in the LTT phase. An important feature is, as shown in Figs. 4(b) and 5, that $La_{1.88}Sr_{0.12}CuO_4$ has larger phononic thermal conductivity than $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ in both the ab plane and the c axis for $T > 45$ K, which means $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ has stronger phonon scattering (which may come from Eu dopants) at high temperatures even in the LTT phase. Therefore, it is more reasonable to attribute the reappearance of phonon peak in Eu-doped LSCO to the stabilization of stripes at low temperatures, which reduces the strong phonon scattering by the stripe fluctuations, rather than the difference of the phonon heat transport between LTT and LTO phases.

By reexamining the previous thermal conductivity data for $La_{1.28}Nd_{0.6}Sr_{0.12}CuO_4$ single crystal,[21] we find that the above feature is also present in Nd-doped LSCO. This means that the suppression of the phonon scattering is common to the R-doped LSCO, where static charge stripes are formed.

Furthermore, by comparing the data of $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ with those of $La_{1.8}Eu_{0.2}CuO_4$, which has LTO2 phase without stripes, we can obtain useful information on the scattering mechanism of phonons. In Figs. 4(a) and 5, one can see that in the ab direction the phonon peak in $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ is larger than that in $La_{1.8}Eu_{0.2}CuO_4$, although the former compound has much more dopants and charge carriers. This difference clearly shows that the LTT phase has stronger phonon transport than the LTO2 phase, which overcomes the additional impurity-phonon scattering by Sr dopants and charge-phonon scattering in $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$. However, the phonon peak in κ_c shows opposite trend, that is, the peak magnitude is larger in $La_{1.8}Eu_{0.2}CuO_4$ than in $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$. The additional phonon scattering in the c axis of $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ is unlikely due to the Sr dopants, considering their negligible effect on κ_{ab}. Instead, it is probably due to the lattice disorder induced by the disordering of static stripes in the c direction.[21] There are two factors that make the stripe correlation in the c direction very weak even in the static stripe phase. First, the neutron experiments have already shown[44] that the magnetic correlation length in the c direction is very short. Second, the stripe orientations have been proposed to rotate 90° from one CuO_2 plane to the nearest-neighbor plane.[44] Such strong disorder of the static stripes along the c axis leads to rather strong phonon scattering in the c-axis transport, which is very similar to what was observed in the lightly doped LSCO.[21]

IV. SUMMARY

We have measured the ab-plane and the c-axis thermal conductivities of $La_{2-y}Eu_yCuO_4$ ($y=0$, 0.02 and 0.2) and $La_{1.88-y}Eu_ySr_{0.12}CuO_4$ ($y=0$ and 0.2) single crystals. It is found that the low-temperature phonon heat transport shows opposite Eu doping dependence in these two systems, that is, Eu doping strongly suppresses the phonon peak in LCO, while it induces the reappearance of phonon peak in LSCO. In Eu-1%-doped LCO, the phonon peak in κ_{ab} is anomalously wiped out, and such strong phonon scattering is caused by the lattice distortions induced by the local LTO2-like regions around Eu ions in the LTO background. Increasing Eu doping in LCO to 10% leads to the LTO→LTO2 structural transition, which reduces the lattice distortion and phonon scattering. The phonon peak, although observed in $La_{1.8}Eu_{0.2}CuO_4$, is still much smaller than that in pure LCO. On the other hand, Eu-doping in LSCO enhances the phonon heat transport, which is likely due to the formation of static stripes that reduces the phonon scattering. Comparison of the phonon heat transport between $La_{1.68}Eu_{0.2}Sr_{0.12}CuO_4$ and $La_{1.8}Eu_{0.2}CuO_4$ tells us that phonon scattering in the c axis is rather strong even in the static stripe phase, which is consistent with the fact that the stripes are not well ordered in the c axis.

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