Heat transport of $\text{La}_{2-y}\text{Eu}_y\text{CuO}_4$ and $\text{La}_{1.88-y}\text{Eu}_y\text{Sr}_{0.12}\text{CuO}_4$ single crystals

X. F. Sun, Seiki Komiya, and Yoichi Ando

Central Research Institute of Electric Power Industry, Komae, Tokyo 201-8511, Japan.

(Dated: March 22, 2022)

PACS numbers: 74.25.Fy, 74.72.Dn

I. INTRODUCTION

In $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO) related compounds, the high-temperature structure is tetragonal (HTT, space group $I4/mmm$) and there are three different low-temperature phases, the LTO (low-temperature orthorhombic, space group $Bmab$) phase in LSCO, the LTO2 (low-temperature orthorhombic 2, space group $Pcna$) phase in $\text{La}_{2-x-y}\text{R}_y\text{Sr}_x\text{CuO}_4$, and LTT (low-temperature tetragonal, space group $P4_2/nmc$) phase in $\text{La}_{2-x-y}\text{R}_y\text{Sr}_x\text{CuO}_4$ with larger $x$. These low-temperature structures are classified by the tilts of CuO$_6$ octahedra around [110] and [110] 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. The static stripe order of charges and spins is only established in R (Nd,Eu)-doped LSCO, where the stripes are believed to be pinned by the particular tilting of CuO$_6$ octahedra in the HTT phase.

It is known that the antiferromagnetic (AF) insulating compound $\text{La}_2\text{CuO}_4$ (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 ($\kappa_{ab}$ and $\kappa_c$). However, the low-$T$ 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. 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 $v_s$ (LTT) $>$ $v_s$ (LTO2) $>$ $v_s$ (LTO), 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; 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: $\text{La}_{2-y}\text{Eu}_y\text{CuO}_4$ ($y = 0, 0.02$
and 0.2) and La$_{1.88-y}$Eu$_y$Sr$_{0.12}$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 $\kappa_{ab}$, 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$_{2-x}$Eu$_x$CuO$_4$ and La$_{1.88-y}$Eu$_y$Sr$_{0.12}$CuO$_4$ are grown by the traveling-solvent floating-zone (TSFZ) technique and carefully annealed. 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 $2.5 \times 0.5 \times 0.15$ mm$^3$, where the c axis is perpendicular or parallel to the platelet with an accuracy of 1°. La$_{2-y}$Eu$_y$CuO$_4$ samples are annealed in flowing pure He gas to remove the excess oxygen. On the other hand, La$_{1.88-y}$Eu$_y$Sr$_{0.12}$CuO$_4$ samples are annealed at 850 °C for 48 hours in air, followed by rapid quenching to room temperature, to remove the oxygen defects.

The thermal conductivity $\kappa$ is measured using a conventional steady-state technique at 2 – 150 K and a modified steady-state technique at 150 – 300 K. The temperature difference $\Delta T$ on the sample is measured by a differential Chromel-Constantan thermocouple, which is glued to the sample using GE7031 varnish. The $\Delta T$ varies between 0.5% and 2% of the sample temperature. To improve the accuracy of the measurement at low temperatures, $\kappa$ is also measured with “one heater, two thermometer” method from 2 to 20 K by using a chip heater and two Cernox chip sensors. 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$_y$CuO$_4$

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$_2$CuO$_4$ sample, as has already been discussed in a previous paper, 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 $\kappa_{ab}$ and $\kappa_c$. 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 next 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 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. 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 $\kappa_{ab}$ 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. When the doping level is too small to induce the macroscopic structural transition, it is most likely that the 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 $\kappa_c$ 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 $\kappa_c$ 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). However, the temperature dependence of $\kappa_c$ 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$_{1.8}$Eu$_{0.2}$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 $\kappa_{ab}$ and $\kappa_c$ of La$_{1.8}$Eu$_{0.2}$CuO$_4$ show a step-like increase at $\sim$ 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.

### B. Magnetic properties of La$_{2-x}$Eu$_x$CuO$_4$

It is well known that the magnetic properties of La$_2$CuO$_4$ 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. 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. 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 $\chi_c$ and a much broader peak in $\chi_{ab}$ at $T_N = 307$ K, which originates from the AF ordering of $\text{Cu}^{2+}$ canted moments.

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 $\chi_c$ and $\chi_{ab}$ 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 $\chi_c$ and noticeably $T$-dependent in $\chi_{ab}$, 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 $k_B T$, as shown for Eu$_2$CuO$_4$.) Second, a clear Néel transition shows up in $\chi_c$ with lower $T_N$ (268 K) compared to undoped LCO, while the corresponding peak is almost smeared out in $\chi_{ab}$ (only a slight hump at $T_N$) because of the strong $T$-dependence of $\chi_{ab}$. Third, another transition appears in $\chi_c$ 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. It is not clear whether there is a corresponding transition in $\chi_{ab}$ 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.

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.

For Eu-1% doping, the susceptibility data show moderate changes. First, the enhancement of both $\chi_c$ and $\chi_{ab}$ are much smaller than those in La$_{1.4}$Eu$_{0.6}$CuO$_4$. Second, 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 $\kappa_{ab}$. (In contrast, the magnon peak disappears in La$_{1.98}$Sr$_{0.02}$CuO$_4$ (Fig. 1), in which the Néel transition also disappears.) Third, there is no second transition in $\chi_c$ at $\sim 130$ K, because there is no structural phase transition in this lightly-doped sample. However, $\chi_c$ decreases slowly with deceasing temperature from $\sim 150$ K to 50 K and $\chi_{ab}$ 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$_{1.08}$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 $\kappa_e$ and the electrical resistivity $\rho$ 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 $2.44 \times 10^{-8} \text{W} \Omega/\text{K}^2$. When the electron-electron correlation becomes strong, $L$ becomes smaller. For YBa$_2$Cu$_3$O$_{7-\delta}$, $L$ has been estimated to be $1.2-2.0 \times 10^{-8} \text{W} \Omega/\text{K}^2$ near $T_c$ by Hirschfeld and Putikka while Takenaka et al. estimated $L$ to be $2.4-3.3 \times 10^{-8} \text{W} \Omega/\text{K}^2$ above $T_c$. So there is still no consensus value of $L$ for cuprates. Here, we roughly estimate $\kappa_e$ of our crystals by using the Sommerfeld value. The in-plane resistivity $\rho_{ab}$ 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 contribution to thermal conductivity is phononic in these samples. For the $c$-axis heat transport, the electronic contribution is negligibly small.

FIG. 3: Magnetic susceptibility of La$_{2-y}$Eu$_y$CuO$_4$ single crystals measured in 5000 Oe field applied along (a) the $c$ axis and (b) the $ab$ plane.
small because of the 2–3 orders of magnitude larger electrical resistivity in the c axis compared to \( \rho_{ab} \).

The experimental data for \( \kappa_c \) is nearly pure phonon conductivity.

Clearly, the phonon heat transport is strongly damped in \( \text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4 \), which shows complete disappearance of the phonon peak in \( \kappa_{ab} \) and a weak hump in \( \kappa_c \). The strong phonon scattering can be related to the Sr dopants 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 \( \kappa_{ab} \) and \( \kappa_c \). 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 polycrys-

![Graph](image1)

**FIG. 4:** Low-temperature thermal conductivity of \( \text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4 \) and \( \text{La}_{1.68}\text{Eu}_{0.2}\text{Sr}_{0.12}\text{CuO}_4 \) single crystals. The data for \( \text{La}_{1.68}\text{Eu}_{0.2}\text{Sr}_{0.12}\text{CuO}_4 \) are also shown for comparison. The step-like feature at \( \sim 130 \text{ K} \) is due to the LTO \( \rightarrow \) LTT and LTO \( \rightarrow \) LTO2 structural transition for \( \text{La}_{1.68}\text{Eu}_{0.2}\text{Sr}_{0.12}\text{CuO}_4 \) and \( \text{La}_{1.8}\text{Eu}_{0.2}\text{CuO}_4 \), respectively.

![Graph](image2)

**FIG. 5:** Comparison of the in-plane phononic thermal conductivity \( \kappa_{ph,ab} \) of \( \text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4 \) single crystal to that of \( \text{La}_{1.68}\text{Eu}_{0.2}\text{Sr}_{0.12}\text{CuO}_4 \) 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 \( \text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4 \) (solid circles) and \( \text{La}_{1.68}\text{Eu}_{0.2}\text{Sr}_{0.12}\text{CuO}_4 \) (open circles).

talline 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 \( \rightarrow \) LTT structural transition takes place at \( \sim 130 \text{ K} \) [Ref. \( 15, 30 \)] and results in a step-like increase of the phononic thermal conductivity in the LTT phase. An important feature is, as shown in Figs. 4(b) and 5, that \( \text{La}_{1.88}\text{Sr}_{0.12}\text{CuO}_4 \) has larger phononic thermal conductivity than \( \text{La}_{1.68}\text{Eu}_{0.2}\text{Sr}_{0.12}\text{CuO}_4 \) in both the \( ab \) plane and the \( c \) axis for \( T > 45 \text{ K} \), which means \( \text{La}_{1.68}\text{Eu}_{0.2}\text{Sr}_{0.12}\text{CuO}_4 \) 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 re-examining the previous thermal conductivity data for \( \text{La}_{1.28}\text{Nd}_{0.6}\text{Sr}_{0.12}\text{CuO}_4 \) single crystal,\(^{28}\) 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 \( \text{La}_{1.68}\text{Eu}_{0.2}\text{Sr}_{0.12}\text{CuO}_4 \) with those of \( \text{La}_{1.8}\text{Eu}_{0.2}\text{CuO}_4 \), 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 \( \text{La}_{1.68}\text{Eu}_{0.2}\text{Sr}_{0.12}\text{CuO}_4 \) is larger than that in \( \text{La}_{1.8}\text{Eu}_{0.2}\text{CuO}_4 \), 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 $\kappa_c$ shows opposite trend, that is, the peak magnitude is larger in La$_{1.68}$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 $\kappa_{ab}$. Instead, it is probably due to the lattice disorder induced by the disordering of static stripes in the $c$ direction. 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 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. 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.

IV. SUMMARY

We have measured the $ab$-plane and the $c$-axis thermal conductivities of La$_{2-y}$Eu$_y$CuO$_4$ ($y = 0, 0.02$ and $0.2$) and La$_{1.88-y}$Eu$_y$Sr$_{0.12}$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 $\kappa_{ab}$ 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 $\rightarrow$ 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.

Acknowledgments

We thank J. Takeya for technical assistance, A. N. Lavrov and I. Tsukada for helpful discussions.

[1] M. K. Crawford, R. L. Harlow, E. M. McCarron, W. E. Farneth, J. D. Axe, H. Chou, and Q. Huang, Phys. Rev. B 44, 7749 (1991).
[2] B. Büchner, M. Breuer, A. Freimuth, and A. P. Kampf, Phys. Rev. Lett. 73, 1841 (1993).
[3] J. M. Tranquada, B. J. Sternlieb, J. D. Axe, Y. Nakamura, and S. Uchida, Nature 375, 561 (1995).
[4] 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).
[5] H. A. Mook, P. Dai, and F. Dogan, Phys. Rev. Lett. 88, 097004 (2002).
[6] S. Wakimoto, G. Shirane, Y. Endoh, K. Hirota, S. Ueki, K. Yamada, R. J. Birgeneau, M. A. Kastner, Y. S. Lee, P. M. Gehring, and S. H. Lee, Phys. Rev. B 60, R769 (1999).
[7] M. Matsuda, M. Fujita, K. Yamada, R. J. Birgeneau, Y. Endoh, and G. Shirane, Phys. Rev. B 65, 134515 (2002).
[8] M. Fujita, K. Yamada, H. Hiraka, P. M. Gehring, S. H. Lee, S. Wakimoto, and G. Shirane, Phys. Rev. B 65, 064505 (2002).
[9] A. W. Hunt, P. M. Singer, K. R. Thurber, and T. Imai, Phys. Rev. Lett. 82, 4300 (1999).
[10] Y. Ando, A. N. Lavrov, and K. Segawa, Phys. Rev. Lett. 83, 2813 (1999).
[11] T. Noda, H. Eisaki, and S. Uchida, Science 286, 265 (1999).
[12] X. J. Zhou, P. Bogdanov, S. A. Kellar, T. Noda, H. Eisaki, S. Uchida, Z. Hussain, and Z.-X. Shen, Science 286, 268 (1999).
[13] V. J. Emery, S. A. Kivelson, and O. Zachar, Phys. Rev. B 56, 6120 (1997).
[14] S. A. Kivelson, E. Fradkin, and V. J. Emery, Nature 393, 550 (1998).
[15] J. Zaanen, Science 286, 251 (1999).
[16] Y. Ando, K. Segawa, S. Komiya, and A. N. Lavrov, Phys. Rev. Lett. 88, 137005 (2002).
[17] B. Nachumi, Y. Fudamoto, A. Keren, K. M. Kojima, M. Larkin, G. M. Luke, J. Merrin, O. Tchernyshyov, Y. J. Uemura, N. Ichikawa, M. Goto, H. Takagi, S. Uchida, M. K. Crawford, E. M. McCarron, D. E. MacLaughlin, and R. H. Heffner, Phys. Rev. B 58, 8760 (1998).
[18] H.-H. Klauss, W. Wagener, M. Hillberg, W. Kopmann, H. Wulf, F. J. Litterst, M. Hückner, and B. Büchner, Phys. Rev. Lett. 85, 4590 (2000).
[19] B. J. Suh, P. C. Hammel, M. Hückner, B. Büchner, U. Ammerahl, and A. Revcolevschi, Phys. Rev. B 61, R9265 (2000).
[20] Y. Nakamura, S. Uchida, T. Kimura, N. Motohira, K. Kishio, K. Kitazawa, T. Arima, and Y. Tokura, Physica C 185-189, 1409 (1991).
[21] X. F. Sun, J. Takeya, S. Komiya, and Y. Ando, Phys. Rev. B 67, 104503 (2003).
O. Baberski, A. Lang, O. Maldonado, M. H"ucker, B. B"uchner, and A. Freimuth, Europhys. Lett. 44, 335 (1998).

M. Sera, M. Maki, M. Hiroi, and N. Kobayashi, J. Phys. Soc. Jpn. 66, 765 (1997).

M. Sera, M. Maki, M. Hiroi, N. Kobayashi, T. Suzuki, and T. Fukase, Phys. Rev. B 52, R735 (1995).

S. Komiya, Y. Ando, X. F. Sun, and A. N. Lavrov, Phys. Rev. B 65, 214535 (2002).

Y. Ando, J. Takeya, Y. Abe, K. Nakamura, and A. Kapitulnik, Phys. Rev. B 62, 626 (2000).

F. Cordero, A. Paolone, R. Cantelli, and M. Ferretti, Phys. Rev. B 62, 5309 (2000).

A. N. Lavrov, S. Komiya, and Y. Ando, Nature 418, 385 (2002); cond-mat/0208013

R. Werner, M. H"ucker, and B. B"uchner, Phys. Rev. B 62, 3704 (2000).

I. Tsukada, X. F. Sun, S. Komiya, A. N. Lavrov, and Y. Ando, cond-mat/0212360

It was reported in Ref. 30 that La_{1.8}Eu_{0.2}O_4 has LTT phase, while the new result on single crystal (Ref. 31) suggests that this compound has LTO2 phase, similar to Nd-doped LCO (Ref. 1).

M. A. Kastner, R. J. Birgeneau, G. Shirane, and Y. Endoh, Rev. Mod. Phys. 70, 897 (1998).

B. Keimer, N. Belk, R. J. Birgeneau, A. Cassanho, C. Y. Chen, M. Greven, M. A. Kastner, A. Aharony, Y. Endoh, R. W. Erwin, and G. Shirane, Phys. Rev. B 46, 14034 (1992).

T. Thio, T. R. Thurston, N. W. Preyer, P. J. Picone, M. A. Kastner, H. P. Jenssen, D. R. Gabbe, C. Y. Chen, R. J. Birgeneau, and A. Aharony, Phys. Rev. B 38, 905 (1988).

R. Werner, M. H"ucker, and B. B"uchner, Phys. Rev. B 56, 5654 (1997).

K. Takenaka, Y. Fukuzumi, K. Mizuhashi, S. Uchida, H. Asaoka, and H. Takei, Phys. Rev. B 56, 5390 (1997).

Y. Nakamura and S. Uchida, Phys. Rev. B 47, 8369 (1993).

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