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Enhanced Phonon Scattering below T_c Caused by Zn and Ni Substitution in $La_{1.85}Sr_{0.15}CuO_4$

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The thermal conductivity κ has been measured for $La_{2-X}Sr_XCuO_4$ and $La_{1.85}Sr_{0.15}Cu_{0.98}M_{0.02}O_4$ (M; Zn, Ni). The characteristic enhancement in κ below T_c was confirmed for $La_{1.85}Sr_{0.15}CuO_4$. The phonon scattering mechanisms were analyzed in detail and the electron-phonon coupling constant λ was estimated to be ~0.05. The κ enhancement becomes indetectable on Zn or Ni substitution for Cu, which indicated survival of the phonon scattering by charge carriers down to lower temperatures as a result of reduced T_c.

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1. INTRODUCTION

The thermal conductivity κ of several high T_c cuprates, typically $YBa_2Cu_3O_7$[1-3], shows a characteristic enhancement below the superconducting transition temperature T_c. In contrast, $La_{2-X}M_XCuO_4$ with T-type structure does not clearly show the corresponding enhancement.[4] In this paper, we present observation of the κ enhancement in $La_{1.85}Sr_{0.15}CuO_4$ and its rapid quenching by a small amount substitution of Cu by Zn and Ni. The origin of the κ enhancement is discussed and the phonon scattering mechanisms are analyzed in detail.

2. EXPERIMENTAL

$La_{2-X}Sr_XCuO_4$ and $La_{1.85}Sr_{0.15}Cu_{0.98}M_{0.02}O_4$ (M; Zn, Ni) samples were prepared by a solid state reaction method. The density of the samples was higher than 90% of the ideal one. The κ measurement was made between 10K and 150K by a continuous heat flow method and the thermal diffusivity α was measured by an arbitrary heating method simultaneously with κ.[5]

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3. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of the electrical resistivity $\rho(T)$ of $La_{2-X}Sr_XCuO_4$ (LSCO) for X=0.10, 0.15 and 0.20. The ρ values decrease with increasing Sr concentration X. The superconducting transition temperature T_c ($=T_c^{end}$) is 31K, 38K and 33K for X=0.10, 0.15 and 0.20, respectively. Figure 2 shows the phonon thermal conductivity κ_{ph} as a function of temperature T. κ_{ph} of LSCO (X=0.15) shows an enhancement below T_c and takes a weak maximum at T~30K. For LSCO (X=0.20), a trace of the κ enhancement below T_c is discernible.

The heat conduction in metals is due to both the electrons (κ_e) and the phonons (κ_{ph}). We assume that the normal state electronic component κ_{en} follows the Wiedemann-Franz law, while that of the superconducting state κ_{es} follows the theory by Kadanoff and Martin[6] with the d-wave energy gap $\Delta=1.5\Delta_{BCS}\cos 2\phi$.[3] We also assume a T^3 dependence of $\rho(T)$ below T_c.[3] κ_e is always much smaller than total κ because of a large residual resistivity $\rho(0)$ ($\geq$0.25mΩcm) as estimated by the extrapolation to T=0K.

The phonon thermal conductivity κ_{ph} ($=\kappa-\kappa_e$) is given by

$$\kappa_{ph}=\frac{3dn_0R<v_s^2>}{2\pi M}\left(\frac{T}{\Theta_D}\right)^3\int_0^{2\pi}d\phi\int_0^{\Theta_D/T}\frac{x^4e^x}{(e^x-1)^2}\tau_{ph}(x)dx \quad , \qquad (1)$$

where n_0(=7) is the number of atoms composing the 214 compounds, R the gas constant, v_s (~3700m/s)[7] the average sound velocity and x is the reduced phonon frequency. Assuming a kind of Matthiesen's rule for the scattering rates, the

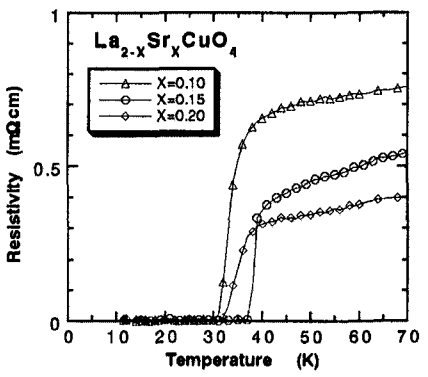

Fig. 1. The temperature dependence of the electrical resistivity $\rho(T)$ of $La_{2-X}Sr_XCuO_4$ (X=0.10, 0.15, 0.20).

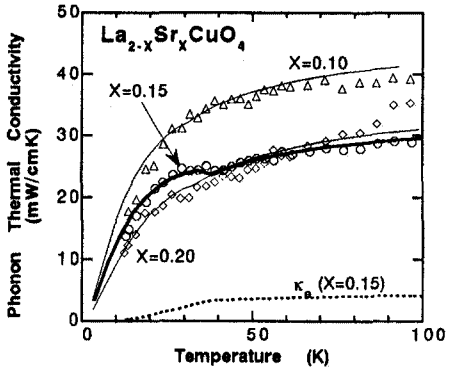

Fig. 2. κ_{ph} vs T of $La_{2-X}Sr_XCuO_4$. The dashed line represents the estimated electronic component κ_e for X=0.15.

phonon relaxation time τ_{ph} is given by

$$\tau_{ph}^{-1} = \tau_b^{-1} + \tau_p^{-1} + \tau_s^{-1} + \tau_e^{-1} + \tau_t^{-1}$$
$$= \tau_b^{-1} + PT^4x^4 + ST^2x^2 + ETxg(x,y) + KTx\tanh\left(\frac{x}{2}\right). \qquad (2)$$

Here, τ_b is the phonon relaxation time due to grain boundaries and P, S and E refer to the strength of the phonon scattering by point defects, sheet-like faults and conduction electrons, respectively.[8] $KTx\tanh(x/2)$ stands for the scattering due to two-level like tunneling states,[9] which was suggested to be operative in this system.[4,10] We assumed that the dynamical phonon scattering of apical oxygens is an important origin of the K term, which comes from the phase instability between LTO and HTT(or LTT) phases. The function, $g(x,y)=\tau_{en}/\tau_{es}$, gives the ratio of the phonon scattering by electrons in the normal and the superconducting states, which depends on the energy gap through the parameter $y=\Delta(T)/k_BT$.[11]

In order to analyze the phonon scattering on the basis of the eqs. (1) and (2), we need the value of the Debye temperature Θ_D. The specific heat C was estimated from the relation $C=\kappa/\alpha$ and an average value of Θ_D =350K was found to be appropriate for all the samples. The data of the $\alpha(T)$ measurement are presented in Fig. 3. $\tau_b=l_b/v_s$ was determined from the average grain size of each sample observed by a SEM. The results of the fitting for κ_{ph} are given by the solid lines in Fig. 2. The determined parameters are summarized in Table I. The calculated κ_{ph} can reproduce the measured κ_{ph} data satisfactorily.

In Table I, the electron-phonon coupling parameter λ is estimated from the relation, $\lambda=2a\langle t\rangle E/\pi v_s$,[12] a=4Å being the lattice parameter and $\langle t\rangle$=5000K, the

Table I. Used and determined parameters in the fitting for κ_{ph} of the $La_{2-X}Sr_XCuO_4$ (X=0.10, 0.15, 0.20) and $La_{1.85}Sr_{0.15}Cu_{0.98}M_{0.02}O_4$ (M; Zn, Ni) samples.

	X=0.10	X=0.15	X=0.20	X=0.15 M=Zn	X=0.15 M=Ni
$\tau_b^{-1}(s^{-1})$	1.7×10^8	3.5×10^8	3.5×10^8	3.4×10^8	3.5×10^8
$l_b(\mu m)$	15.7	7.8	7.7	7.9	7.7
$S\,(K^{-2}s^{-1})$	2.7×10^6	3.0×10^6	1.0×10^7	2.8×10^6	2.8×10^6
$P\,(K^{-4}s^{-1})$	7.6×10^3	8.1×10^3	5.9×10^3	6.0×10^3	5.4×10^3
$E\,(K^{-1}s^{-1})$	1.9×10^7	1.4×10^8	7.6×10^7	1.4×10^8 *	1.4×10^8 *
$K\,(K^{-1}s^{-1})$	3.3×10^8	3.8×10^8	5.2×10^8	8.9×10^8	9.9×10^8
λ	0.01	0.05	0.03	(0.05)	(0.05)
T_c (K)	31	38	33	16	19

* E value for X=0.15(M=Zn) and X=0.15(M=Ni) is assumed to be the same as that of the non-doped $La_{2-X}Sr_XCuO_4$.

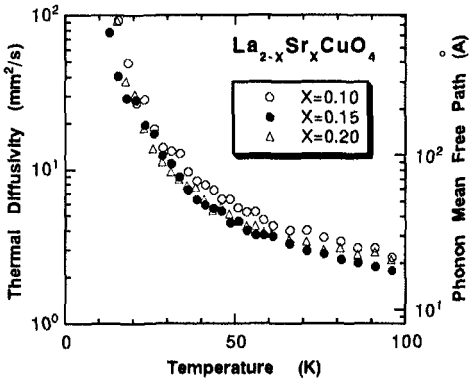

Fig. 3. Thermal diffusivity $\alpha(T)$ of $La_{2-X}Sr_X$-CuO_4.The right hand ordinate provides a rough measure for the phonon mean free path l_{ph}.

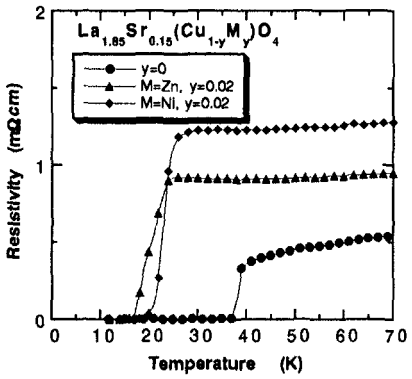

Fig. 4. ρ vs T for $La_{1.85}Sr_{0.15}Cu_{0.98}$-$M_{0.02}O_4$ (M; Zn, Ni).

effective matrix element for the electron hopping in the CuO_2 plane. The obtained λ value is 0.05 for $La_{1.85}Sr_{0.15}CuO_4$. The origin of the pretty clear enhancement of κ for this compound is explained as to come from κ_{ph} similarly to that of the sintered $YBa_2Cu_3O_{7-\delta}$ system (λ~0.4 and ~0.15 for 90K- and 60K-phase $YBa_2Cu_3O_{7-\delta}$[3]).

Figure 4 shows ρ(T) of $La_{1.85}Sr_{0.15}Cu_{0.98}M_{0.02}O_4$ (M; Zn, Ni) and Fig. 5(a) shows $\kappa_{ph}(T)$ of the same samples. By substituting Zn (non-magnetic) or Ni (magnetic) for Cu by only 2%, T_c is drastically depressed. The depression effect is somewhat more conspicuous for Zn (T_c=16K) than Ni (T_c=19K). In Fig. 5(a), the behaviors of $\kappa_{ph}(T)$ for LSCO (2% Zn) and LSCO (2% Ni) are quite similar and almost indistinguishable. In comparison to $\kappa_{ph}(T)$ of non-substituted $La_{1.85}Sr_{0.15}CuO_4$, $\kappa_{ph}(T)$ of

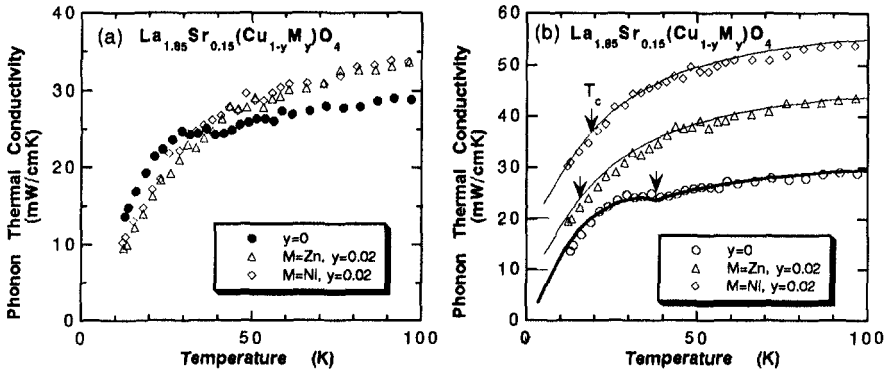

Fig. 5 (a) κ_{ph} vs T for $La_{1.85}Sr_{0.15}Cu_{0.98}M_{0.02}O_4$ (M; Zn, Ni). (b) The fitting results for the samples. The origin of the y axis is shifted by 10mW/cmK for each sample.

Zn and Ni substituted LSCO is larger for $T \geq 35$K, which is, however, strongly surpressed below $T<35$K. The results of the fitting and the determined parameters are presented by solid lines in Fig. 5(b) and in Table I, respectively. These fittings suggest that the phonon-electron scattering term ($ET^{x}g(x,y)$ in eq.(2)) remains effective down to lower temperatures in the Zn and Ni substituted LSCO samples owing to the depression of T_c.

4. SUMMARY

The thermal conductivity $\kappa(T)$ of sintered $La_{2-X}Sr_XCuO_4$ (X=0.10, 0.15, 0.20) and $La_{1.85}Sr_{0.15}Cu_{0.98}M_{0.02}O_4$ (M; Zn, Ni) has been measured and the phonon scattering mechanisms in these compounds have been analyzed.

(1) $La_{1.85}Sr_{0.15}CuO_4$ showed the κ enhancement below T_c. The enhancement is attributable to the phonon component κ_{ph}, and the electron-phonon coupling parameter was determined to be $\lambda \sim 0.05$ from the size of the enhancement.

(2) The large residual electrical resistivity $\rho(0)$ excluded the electronic origin for the κ enhancement in the present sintered samples.

(3) By substituting Zn or Ni for Cu by 2%, the enhancement in κ_{ph} became indetectable. κ_{ph} of Zn or Ni substituted LSCO was more strongly depressed than that of the non-substituted mother compound below T<35K. This is because the phonon scattering by electrons still survives down to lower temperatures owing to the reduced transition temperature T_c caused by the substitution.

(4) The effect of the non-magnetic Zn substitution and that of magnetic Ni substitution on the thermal conductivity are very similar.

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