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Effect of Y-site and Ba-site Substitution on Thermal Properties of $YBa_2Cu_3O_{7-\delta}$

Hiroyuki Fujishiro, Kiminari Nakasato, Shigeo Takahashi and Manabu Ikebe

Faculty of Engineering, Iwate University, 4-3-5, Ueda, Morioka 020, Japan

The effect of partial replacement of Y site with Ca or Ba site with Sr on the thermal and electrical properties of $YBa_2Cu_3O_{7-\delta}$ superconductors was investigated. For $Y(Ba_{1-X}Sr_X)_2Cu_3O_{7-\delta}$ system, the characteristic enhancement of the thermal conductivity $\kappa(T)$ below the transition temperature T_c was decreased more slowly by substitution than that for $(Y_{1-X}Ca_X)Ba_2Cu_3O_{7-\delta}$ system. Electron-phonon interaction in these systems were discussed based on the phonon heat conduction model under the weak coupling d-wave energy gap.

1. INTRODUCTION

A characteristic feature of thermal conductivity $\kappa(T)$ in $YBa_2Cu_3O_{7-\delta}$ (YBCO) superconductors is a rapid rise just below T_c with decreasing temperature T and existence of a maximum at about $T_c/2$. The origin of this bump is under controversy between the phonon and the carrier model. We have investigated the effects of oxygen deficiency δ and Zn impurity of Cu site on $\kappa(T)$ and the experimental results have been systematically analyzed on the basis of the phonon heat conduction model [1,2]. It has been reported that the Y site replacement with Ca has the effects of increasing the planar hole concentration [3] and that the Ba site replacement with Sr changes the oxygen non-stoichiometry and the copper valence [4]. In this paper, the effect of partial replacement of Y site with Ca or Ba site with Sr on the thermal properties of YBCO is investigated. The variation of phonon scattering is discussed for various Ca or Sr concentrations on the basis of the additive relaxation rate approximation.

2. EXPERIMENTAL

$(Y_{1-X}Ca_X)Ba_2Cu_3O_{7-\delta}$ $(0\le X\le 0.3)$ and $Y(Ba_{1-X}Sr_X)_2Cu_3O_{7-\delta}$ $(0\le X\le 0.4)$ samples were prepared from stoichiometric mixtures of Y_2O_3, $CaCO_3$, $BaCO_3$, $SrCO_3$ and CuO raw powders. The mixtures were calcined at 910°C for 24h in air. They were pulverized, pressed into pellets and then sintered at 955°C for 30h in flowing oxygen. All samples were confirmed to be a single (123) phase by the x-ray diffraction method. The density of these samples was about 90% and was independent of the Ca or Sr concentration. The thermal conductivity (κ) measurement was made by a continuous heat flow method and the thermal diffusivity (α) measurement was performed by an arbitrary heating method quasi-simultaneously. An automated measuring apparatus was used with Au(0.07at.%Fe)-chromel thermocouples as thermometers between 10 and 200K [5].

3. RESULTS AND DISCUSSION

Fig. 1 shows the electrical resistivity ρ vs. T for typical substituted samples. The inset in Fig. 1 shows the transition temperature T_c vs. the concentration X of Ca and Sr. T_c of $Y(Ba_{1-X}Sr_X)_2Cu_3O_{7-\delta}$ system decreased linearly with increasing Sr concentration X. In $(Y_{1-X}Ca_X)Ba_2Cu_3O_{7-\delta}$ system, T_c decreased more rapidly for $X<0.2$ than that of Sr substitution and seemed to become almost constant at $X=0.2\sim0.3$. Similar results have been reported by other workers [6]. Fig. 2 shows the temperature dependence of κ. For $Y(Ba_{1-X}Sr_X)_2Cu_3O_{7-\delta}$ system, the κ enhancement was reduced more moderately by substitution than for $(Y_{1-X}Ca_X)Ba_2Cu_3O_{7-\delta}$ system.

Generally the heat transport is due to both electrons (κ_e) and phonons (κ_{ph}). In the superconducting state, we assume that the electronic component κ_{es} follows the theory proposed by Kadanoff and Martin [7]. We also assume the d-wave energy gap anisotropy $\Delta=\Delta_{max}\cos 2\theta$ with $2\Delta_{max}/k_BT_c=7$ ($\Delta_{max}/\Delta_{BCS}=2$) in the weak coupling

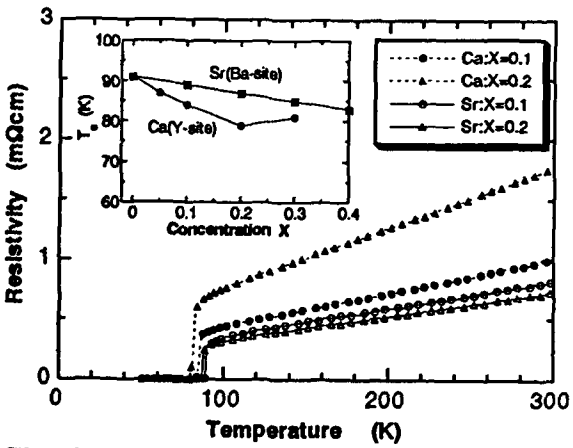

Fig.1 The electrical resistivity ρ vs. T and the transition temperature T_c vs. the concentration X (in the inset).

Table I. Summary of fitting parameters by TW theory for $(Y_{1-X}Ca_X)Ba_2Cu_3O_{7-\delta}$ and $Y(Ba_{1-X}Sr_X)_2Cu_3O_{7-\delta}$ systems.

samples	T_c(K)	τ_B^{-1}(sec^{-1})	l_B(μm)	p(K^{-4}sec^{-1})	s(K^{-2}sec^{-1})	E(K^{-1}sec^{-1})	λ
$YBa_2Cu_3O_{7-\delta}$	91	2.3x10^8	14.3	533	2.2x10^6	7.8x10^8	0.30
$(Y_{0.9}Ca_{0.1})Ba_2Cu_3O_{7-\delta}$	83	1.6x10^9	2.1	2387	2.1x10^6	2.5x10^8	0.10
$(Y_{0.8}Ca_{0.2})Ba_2Cu_3O_{7-\delta}$	79	1.4x10^9	2.3	3681	2.8x10^6	7.2x10^7	0.03
$(Y_{0.7}Ca_{0.3})Ba_2Cu_3O_{7-\delta}$	81	1.6x10^9	2.1	5635	2.5x10^6	7.0x10^7	0.03
$Y(Ba_{0.9}Sr_{0.1})_2Cu_3O_{7-\delta}$	89	9.7x10^8	3.4	1000	5.8x10^6	8.5x10^8	0.32
$Y(Ba_{0.8}Sr_{0.2})_2Cu_3O_{7-\delta}$	87	2.6x10^9	1.3	1972	4.1x10^6	8.7x10^8	0.33
$Y(Ba_{0.7}Sr_{0.3})_2Cu_3O_{7-\delta}$	85	3.1x10^9	1.1	1987	8.6x10^6	7.3x10^8	0.28

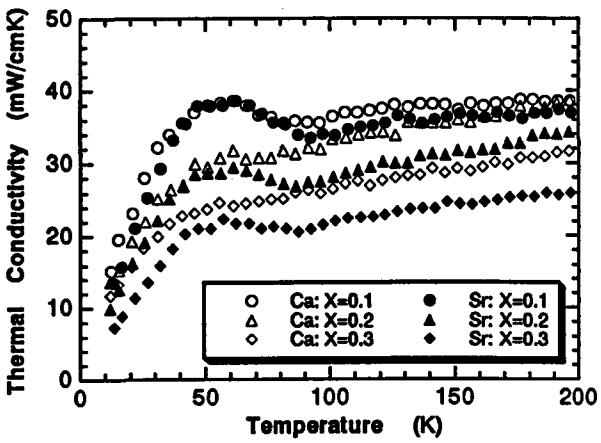

Fig. 2. Temperature dependence of the thermal conductivity κ for various Ca and Sr concentrations.

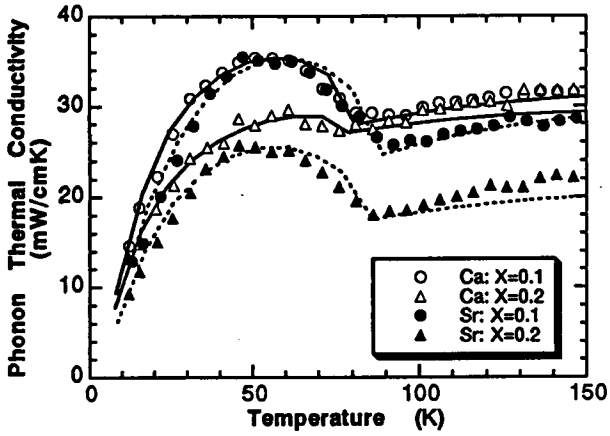

Fig. 3. Examples of the fitting curves by TW theory.

limit [8]. In order to calculate κ_{phs} in the superconducting state, τ_{phs} is assumed to be given by [9],

$$\tau_{phs}^{-1} = \tau_b^{-1} + sT^2x^2 + pT^4x^4 + ETxg, \qquad (1)$$

where τ_b, s, p and E refer to the phonon scattering strength by grain boundary, sheet-like faults, point defects and the charge carriers, respectively. The function $g=\tau_{phn}/\tau_{phs}$ is the ratio of the phonon-electron scattering rate in the normal and superconducting state and was calculated under the assumption of the weak coupling d-wave gap. Table I shows the values of these characteristic parameters determined in the analyses. Fig. 3 shows the examples of the fitting curves, which reproduced the κ_{phs} ($=\kappa-\kappa_{es}$) data satisfactorily. It was found that point defect scattering (p parameter) increased remarkably with increasing substitution concentration X. In $(Y_{1-X}Ca_X)Ba_2Cu_3O_{7-\delta}$, electron-phonon coupling parameter λ ($\propto$E) decreased rapidly with X, but not so rapidly as $YBa_2(Cu_{1-X}Zn_X)_3O_{7-\delta}$ previously studied [2]. In marked contrast, λ remained almost constant of X in $Y(Ba_{1-X}Sr_X)_2Cu_3O_{7-\delta}$. It is noteworthy that T_c reduction is more conspicuous in $(Y_{1-X}Ca_X)Ba_2Cu_3O_{7-\delta}$ system in which the reduction λ is also more salient. From the estimation of the specific heat C using the relation $C=\kappa/\alpha$, a tendency of slight reduction of the Debye temperature Θ_D was noted in both substituted systems. The details of the behavior of C is to be reported elsewhere.

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