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In-plane thermal conductivity of $Ln_{2-x}Ce_xCuO_{4-y}$ single crystals (Ln = Nd and Pr) with the T'-phase structure

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The in-plane thermal conductivity κ_{ab} of $Ln_{2-x}Ce_xCuO_{4-y}$ single crystals (Ln=Nd and Pr) with the T'-phase structure have been measured from 15 K to 150 K. At the lower temperature the measured thermal conductivities show a remarkable enhancement not associated with the superconducting transition but with the decrease of phonon-phonon scattering. The maximum value of the thermal conductivity κ_{max} for the annealed crystal is smaller than κ_{max} for the as-grown crystal because the heat treatment introduced point-defects. Such a behavior in the thermal transport has been discussed, applying a relaxation time approximation to phonon transport. Moreover, from a view point of the apical oxygen atoms the κ data of the 2-1-4 system with the T'-phase structure are compared with the previous data of the $La_{2-x}Sr_xCuO_{4-y}$ single crystal with the T-phase structure.

1. INTRODUCTION

It is well known that the $Ln_{2-x}Ce_xCuO_{4-y}$ system (Ln=Nd and Pr) with the T'-phase structure is a electron-doped high-Tc superconductor while the $La_{2-x}Sr_xCuO_{4-y}$ (LSCO) system with the T-phase structure is a hole-doped superconductor. In thermal transport studies on high-Tc superconductor, whether the two-systems show similar behavior or not is a very interesting problem. In this paper, the in-plane thermal conductivities (κ_{ab}) of $Nd_{2-x}Ce_xCuO_{4-y}$ (NCCO) and $Pr_{2-x}Ce_xCuO_{4-y}$ (PCCO) single crystals in the temperature range from 15 K to 150 K are reported and analyzed on the basis of a relaxation time approximation.

2.EXPERIMENT

The measured single crystals with high quality were prepared by the flux method [1]. Superconductivity was induced in samples by annealing in Ar for 950 °C × 10~20 h. The electrical resistivity of annealed crystals for NCCO and PCCO systems showed supercoductivity with $T_{c\ on}$ = ~18 K and ~24 K, respectively. The thermoelectoric power measurement of the superconducting samples strongly supported that charge carrier in both crystals is electron. The thermal conductivity measurement was made using a steady state method. In our measurements, a fully automated measuring system for thermal conductivity with a helium refrigerator was used. The platelike crystals were typically $a \times b \times c \sim 5 \times 5 \times 1\ mm^3$.

3. RESULTS AND DISCUSSION

The in-plane thermal conductivities of NCCO and PCCO single crystals are shown in Figs.1 and 2, respectively. It is found that the behavior of κ_{ab} in the NCCO system is almost similar in temperature dependence to that in the PCCO system for as-grown crystal or annealed one. A remarkable enhancement is commonly observed in the both systems and is not associated with the superconducting transition. The higher and sharper peak of κ_{ab} in the as-grown sample indicates more perfection of the measured crystal and such a behavior is like to that of ideal insulator. The heat treatment in reduction gas yields suppression of κ_{max} for the annealed crystal. The electronic thermal conductivities of two systems are estimated to be less than ~1 % of total values using the Wiedemann-Franz law from resistivity measurements. Thus, thermal carrier is mainly phonon for both NCCO and PCCO samples. Next, phonon thermal conductivity is discussed applying a relaxation-time approximation.

$$\kappa_p = AT^3 \int_0^{\Theta/T} \frac{x^4 e^x}{(e^x - 1)^2} \tau\, dx$$

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where A , Θ and τ are a proportional constant , the Debye temperature and the relaxation time of phonon. In this calculation, phonon scatterers are considered to be boundaries, point-defects, sheetlike faults and other phonons . The detail expressions in this analysis are referred in [2]. In fitting procedure of the annealed sample, the scattering parameters corresponding to crystal imperfections are enhanced compared with those of the as-grown but the other parameters are fixed. The relaxation time of phonon-phonon scattering is calculated using a expression of exp(-Θ/T) type. The theoretical curves are in good agreement with the measured data for the both systems as shown in Figs 1 and 2, where the solid-lines denote the fitted curves. The lower κ_{max} means the larger cross-section of phonon scattering by crystal imperfections such as oxygen-deficiencies. Furthermore, at low temperatures remarkable enhancement is qualitatively described by decrease of phonon-phonon scattering with decreasing temperature.

Finally, the present data are compared with the previous data of the LSCO system [3]. The data of LSCO single crystal show quite different behavior from those of NCCO and PCCO system as quoted in Fig. 3. It is noted that the LSCO sample was a superconducting crystal with high-quality as well as the measured samples . Thus, apart from crystal imperfections additional scatterer is necessary to explain such a behavior . Phonon scattering by charge carriers is ignored since the clear anomaly of κ in the superconducting state is not observed in previous data . As a new scatterer, two-level tunneling state (TS) is introduced in this calculation. The relaxation time of phonon by TS scattering is proportional to Pωtanh(hω/2kT), where ω and P mean phonon frequency and the density of tunneling state [4]. A fitted curve shown in Fig.3 reproduces the κ data of LSCO. The calculation result is also shown using same scattering parameters except that the TS scattering is absent. This fitted curve approaches to the NCCO and PCCO behavior. Thus, the thermal transport of the 2-1-4 system with the T-phase structure is probably related to the TS scattering. The structural difference between the T and T' phases is attributed to the presence of the apical oxygen atoms in the former. Therefore, it is suggested that the apical oxygen atoms in the T-phase play a significant role for the TS scattering .

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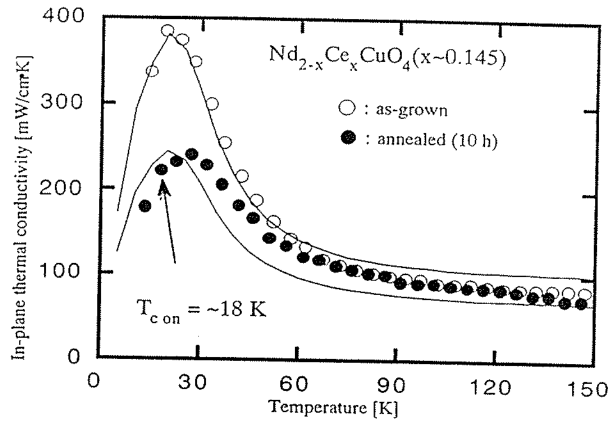

Figure 1 Temperature dependence of κ_{ab} of NCCO single crystal. Solid lines denote fitted curves.

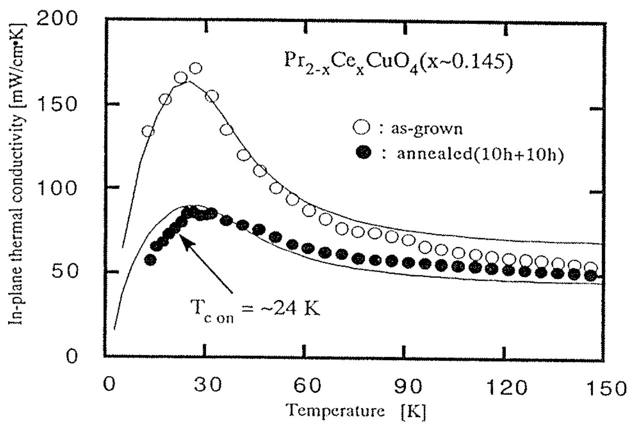

Figure 2 Temperature dependence of κ_{ab} of PCCO single crystal. Solid lines denote fitted curves.

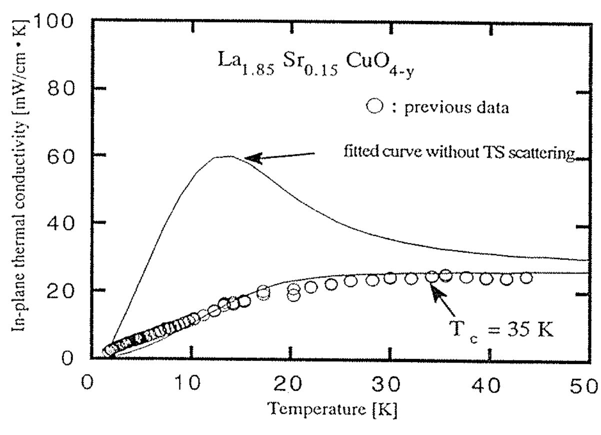

Figure 3 Temperature dependence of κ_{ab} of LSCO single crystal. Solid lines denote fitted curves.

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