

Thermal Conductivity of Bi-2212 Single Crystals Prepared by TSFZ Method

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The in-plane thermal conductivity $\kappa_{ab}(T)$ was measured between 10 and 200K on a $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ (Bi-2212) single crystal, which was grown by traveling solvent floating zone method and heat treated in vacuum and in oxygen atmosphere. The conductivity change on each stage can be explained based on Tewordt-Wölkhausen theory with phonons as the main heat carrier.

1. INTRODUCTION

For the investigation of the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ (Bi-2212) systems, traveling solvent floating zone (TSFZ) method is a valuable method to fabricate large single crystals. One group (Kobe Steel Ltd.) of authors have fabricated Bi-2212 large single crystals using this method [1,2] which have a sufficient size for the thermal conductivity measurement. In this paper, we report the in-plane thermal conductivity $\kappa_{ab}(T)$ of the Bi-2212 single crystal grown by TSFZ method and that of the same crystal after sequential heat-treatments in vacuum and in oxygen atmosphere. The conductivity of the crystal is analyzed based on Tewordt-Wölkhausen theory [3] and the scattering mechanisms of phonon were discussed.

2. EXPERIMENTAL

The measured sample has the composition of $\text{Bi}_{2.24}\text{Sr}_{1.80}\text{Ca}_{0.98}\text{Cu}_{1.94}\text{O}_{8.27}$ with laminar structure consisting of several thin single crystals parallel to the ab-plane. The as-grown sample (#1 stage) has a size of $3.3 \times 1.1 \times 11.0 \text{ mm}^3$ in which the $3.3 \times 11.0 \text{ mm}^2$ plane is an ab-plane. This as-grown sample was heat treated at 600°C for 5h in vacuum (#2 stage) and subsequently heat treated at 650°C for 100h in oxygen atmosphere (#3 stage). The electrical resistivity, the c-axis lattice constant and the thermal conductivity was measured at each stage. The thermal conductivity was measured by a steady state heat flow method [4].

3. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of the thermal conductivity $\kappa_{ab}(T)$ of the crystal at each stage. The electrical resistivity of the as-grown crystal (#1) showed the metallic behavior with rather high resistivity value and somewhat broader resistive transition was seen around 80K. The heat-treatment in vacuum (#2) changed the electrical resistivity to the semiconductive one and completely wiped out the enhancement of the thermal conductivity just below T_c . When the same crystal was heat-treated in oxygen atmosphere (#3), the crystal recovered the metallic electrical behavior with relatively small resistivity values and with double resistive transitions around 80K and 110K. For #3 the thermal conductivity enhancement below 80K became clearer than #1. The electron contribution (κ_{ab}^e) for the thermal

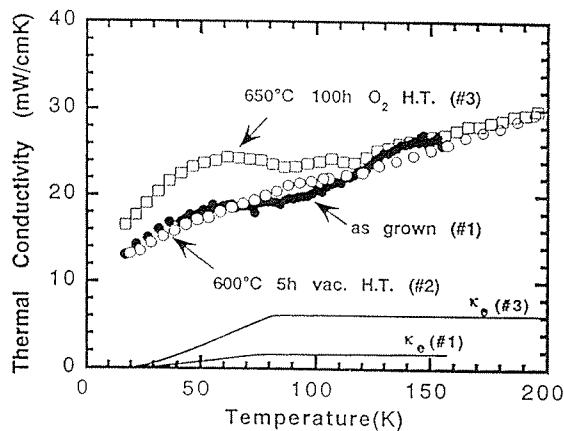


Figure 1 Temperature dependence of the thermal conductivity $\kappa_{ab}(T)$ at each stage.

conductivity was estimated by the Wiedemann-Franz law above T_c and by numerically calculating Kadanoff's expression [5] below T_c which was also shown in Fig. 1. As one can see, the phonon contribution is dominant at each stage of the heat-treatment. The changes of the thermal conductivity and the electrical resistivity behavior were confirmed to be almost reproducible and reversible by further successive heat treatments. The reversibility was also confirmed by measuring the c-axis lattice constant. These reversibilities seem to correspond to the reversibility of the oxygen content in the crystal.

Figure 2 shows the temperature dependence of the phonon thermal conductivity $\kappa_{ab}^{ph}(T)$ of the sample at #2 and #3 stages obtained from the relation of $\kappa_{ab}^{ph} = \kappa_{ab} - \kappa_{ab}^e$. κ_{ab}^{ph} was analyzed using the following equation [3],

$$\kappa_{ph} = \frac{3dnRT^3v^2}{M\Theta_D^3} \int_0^{\Theta_D/T} \frac{x^4 e^x}{(e^x - 1)^2} \tau_{ph} dx, \quad (1)$$

where d ($=6.71\text{g/cm}^3$) is the mass density, M ($=920.7\text{g}$) the molar weight of the sample, n the number of atoms per mole, R the gas constant, and x is the reduced phonon frequency, respectively. $\Theta_D=400\text{K}$ was used as the Debye temperature. The total phonon scattering time τ_{ph} is given by

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

where τ_b is the phonon scattering time due to grain boundary and s , p and E refer to the phonon

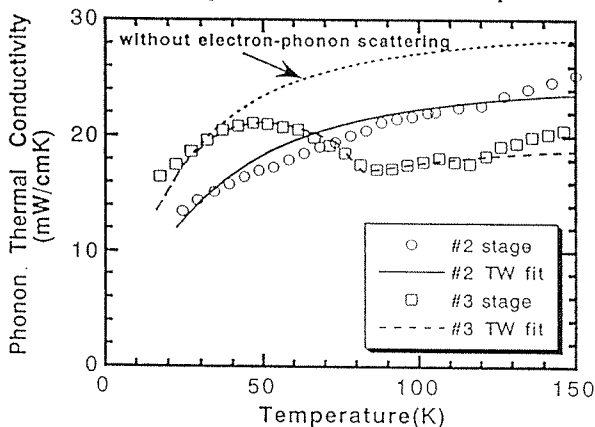


Figure 2 Temperature dependence of the phonon thermal conductivity $\kappa_{ab}^{ph}(T)$ and the TW fitting at #2 and #3 stage.

Table I

Characteristic parameters of the Bi-2212 sample

parameters	#2 stage (600°C 5h in vacuum)	#3 stage (650°C 100h in oxygen)
$T_c(\text{K})$	-	82
$\tau_b^{-1}(\text{sec}^{-1})$	7.0×10^8	7.0×10^8
$p(\text{K}^{-4}\text{sec}^{-1})$	2.7×10^3	3.4×10^3
$s(\text{K}^{-2}\text{sec}^{-1})$	1.3×10^7	6.3×10^6
$E(\text{K}^{-1}\text{sec}^{-1})$	~ 0	3.4×10^8
λ	~ 0	1.5×10^{-1}
$v(\text{msec}^{-1})$	2930	2930
Θ_D	400	400

scattering strength by sheet-like faults, point defects and the charge carriers, respectively. The function $g = \tau_{ph}^n / \tau_{phs}$ is the ratio of the phonon-electron scattering rate in the normal and superconducting states. The calculated κ_{ab}^{ph} using Eqs.(1) and (2) and the parameter values in Table I reproduced the measured $\kappa_{ab}^{ph}(T)$ satisfactorily, as shown in Fig. 2. Figure 2 also shows the estimated κ_{ab}^{ph} curve in the complete absence of the electron-phonon scattering for #3 stage. Comparing the #2 and #3 stage, the point defect scattering is almost the same strength, but the scattering strength due to sheetlike fault of #3 stage is diminished to about a half of #2 stage. The electron-phonon coupling constant λ , which was proportional to the phonon scattering strength by the charge carriers E , was 1.5×10^{-1} for the #3 stage. This λ value is very small in comparison with other results on sintered oxide samples (typically $\lambda=0.7$ by the similar estimation). We consider the estimated small λ value of the present TSFZ single crystal is due to the two step superconducting transition and the inhomogeneous distribution of the oxygen vacancies.

REFERENCES

- 1) I. Shigaki et al., Jpn. J. Appl. Phys. 29 (1990) L2013.
- 2) I. Shigaki et al., Cryo. Eng. 27 (1992) 158.
- 3) L. Tewordt and T. Wölkhausen, Solid State Commun. 70 (1989) 839.
- 4) N. Hobara et al., Cryo. Eng. 28 (1993) 688.
- 5) L.P. Kadanoff and P.C. Martin, Phys. Rev. 124 (1962) 670.