Physica C 468 (2008) 1428–1430

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

# Anisotropic thermal conductivity of Er–Ba–Cu–O bulk superconductors

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ARTICLE INFO

*Article history:*
Available online 12 June 2008

*PACS:*
74.25.Fy
74.72.Jt

*Keywords:*
Thermal conductivity
Er–Ba–Cu–O bulk superconductors
Anisotropy

ABSTRACT

We have measured the temperature dependences of the thermal conductivity in the *ab*-plane, $\kappa_{ab}(T)$, and along the *c*-axis, $\kappa_c(T)$, respectively, for the Er–Ba–Cu–O bulk superconductors, which were fabricated by a method of the melt texture growth. Above the critical temperature $T_c$, the $\kappa_{ab}$ decreases quite moderately as increasing temperature or is almost independent of the temperature. Below the $T_c$, the well-known enhancement is observed but is relatively small. The $\kappa_c(T)$ shows the small absolute values and we found that the anisotropy of the thermal conductivity ($\kappa_{ab}/\kappa_c$) for Er–Ba–Cu–O bulks is of about 2–6.


## 1. Introduction

Thermal conductivity, $\kappa$, is one of the important physical properties for designing the superconducting applications; for instance, it is used for estimating the heat intrusion through the superconducting current lead. Since the high temperature superconducting bulks have high potential for various practical applications, we have measured the thermal conductivity, $\kappa$, at wide temperatures (4–300 K) on various RE–Ba–Cu–O bulk superconductors (RE = rare earth elements) and found that the behaviors of the temperature dependence of the thermal conductivity, $\kappa(T)$, depend strongly on the kind of RE [1,2]. The $\kappa$ for RE = Y, Gd increases with decreasing temperature with a negative curvature above the critical temperature $T_c$. Since the main heat carriers are phonons, it is interpreted that such temperature dependence originates from the fact that the phonon–phonon Umklapp scattering dominates the heat transfer. In the superconducting state, the $\kappa(T)$ shows a broad peak, which is well-known feature in high temperature superconductors [3]. For RE = Sm, Nd, the $\kappa$ is almost independent of the temperature in the normal state and the enhancement below the $T_c$ is somewhat suppressed, which is interpreted to come from the substitution between the RE and Ba sites. Recently, we found rather anomalous behaviors in $\kappa(T)$ of the Dy–Ba–Cu–O bulks [4]. The magnitude is a half or one-third of that of the Y–Ba–Cu–O bulks and the enhancement is also pretty small; furthermore, the $\kappa(T)$ has a positive slope in the normal state.

We measured the temperature dependences of thermal conductivity in the *ab*-plane, $\kappa_{ab}(T)$, and along the *c*-axis, $\kappa_c(T)$, for Er–Ba–Cu–O bulk superconductors. We found that the $\kappa_{ab}(T)$ shows a quite moderate negative slope or almost *T*-independent behavior in the normal state. The absolute values of the $\kappa_{ab}$ are larger than those of the Dy–Ba–Cu–O bulks in the whole measuring temperatures, but are smaller than those of other RE–Ba–Cu–O bulks. The $\kappa_c$ shows small values and we found that the anisotropy of $\kappa_{ab}(T)$ and $\kappa_c(T)$ for Er–Ba–Cu–O bulks is estimated to be of about 2–6.

## 2. Experimental

Er–Ba–Cu–O bulks, which consist of the superconducting matrix phase $ErBa_2Cu_3O_{7-\delta}$ (Er123) and the nonsuperconducting secondary phase $Er_2BaCuO_5$ (Er211), were fabricated by a method of the melt texture growth [5]. Two types of Er–Ba–Cu–O bulks were fabricated; the Er211 powders were ball-milled and not ball-milled. The former composition ratio of the Er123 to the Er211 was 1:0.33 and the latter one was 1:0.5. We added 0.5 wt% Pt powders in both samples. We prepared the rectangular shaped samples by cutting the as-grown bulk crystals; note that we used the region at around the seed crystal. To control the amount of the oxygen deficiency $\delta$ in the Er123 phase, the rectangular samples were annealed at $T_{an}$ = 400–500 °C for 168–240 h in 1 bar flowing oxygen gas. The superconducting transition temperature of samples were of about 89 K, which was defined at the temperature where the

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doi:10.1016/j.physc.2008.05.262

electrical resistivity becomes to the zero. The thermal conductivity was measured by a conventional steady-state heat flow method; the temperature gradient of the sample was estimated by measuring the two temperatures of the sample using chromel–constantan thermocouples. The temperature of the sample stage was controlled from 10 to 250 K using a Gifford–McMahon cycle helium refrigerator. The electrical resistivity was measured by a conventional four-terminal method with a typical current density of about 0.1 A/cm$^2$.

## 3. Results and discussion

Fig. 1 shows the temperature dependence of the *ab*-plane and *c*-axis thermal conductivity for the Er–Ba–Cu–O bulk superconductors ($T_{an}$ = 450 °C) with the ball-milled (BM) and the non ball-milled (nonBM) Er211 particles, respectively. The $\kappa_{ab}$ for the Er–Ba–Cu–O (BM) increases quite moderately with decreasing temperature in the normal state, on the other hand that for the Er–Ba–Cu–O (nonBM) seems to be almost temperature independent. Both show the broad peak below the $T_c$, but the peak is very small in comparison with that observed in other RE–Ba–Cu–O bulks except for RE = Dy. The absolute $\kappa_{ab}$ values of the Er–Ba–Cu–O(BM) are smaller than those for Er–Ba–Cu–O(nonBM), which is explained qualitatively by the fact that the size of Er211 particles is smaller, the effective cross section for the heat carrier scattering becomes larger. Note that the composition ratio (Er123:Er211) cannot give the discrepancy between the $\kappa_{ab}$ values of both Er–Ba–Cu–O bulks, because it was shown that the $\kappa_{ab}$ values of both Sm–Ba–Cu–O and Gd–Ba–Cu–O bulks hardly depend on the composition ratio in the case of the high RE211 content (RE211/RE123 $\geqslant$ 0.3) [2]. We also found that the absolute $\kappa_{ab}$ values for both Er–Ba–Cu–O bulks are rather smaller than those of other RE–Ba–Cu–O bulks except for Dy–Ba–Cu–O. It is well-known that the similar small $\kappa$ values were observed in RE–Ba–Cu–O bulks (RE = Sm, Nd) grown in air [1]. In this case, a part of the RE ions is substituted for a Ba site, which gives rise to form the $RE_{1+x}Ba_{2-x}Cu_3O_{7-\delta}$-type solid solution, because both ionic radii are comparable. This migration enhances the weak superconducting regions which work as the phonon scattering centers, thus the thermal conductivity should be suppressed strongly. Such reduction in $\kappa$ has not been observed in bulks for RE = Y [1], meaning that the substitution between the Y and Ba sites does not occur. Since the ionic radius of $Er^{3+}$ is smaller than that of $Y^{3+}$, the similar substitution between the Er and Ba sites does not occur and this scenario cannot be applicable for Er–Ba–Cu–O bulks; the origin of the small $\kappa_{ab}$ remains an unsolved question.

The $\kappa_c$ for the Er–Ba–Cu–O(BM) increases with decreasing temperature and takes a very broad peak at around 50 K. The anisotropy of the thermal conductivity $\Gamma_k(=\kappa_{ab}/\kappa_c)$ for the Er–Ba–Cu–O(BM) is of about 2, which is comparable to that of other RE–Ba–Cu–O bulks ($\Gamma_k = 2-3$) [1]. On the other hand, we find no anomaly in the $\kappa_c(T)$ for the Er–Ba–Cu–O(nonBM) and the $\Gamma_k$ is estimated to be of about 6. As reported in Ref. [6], the $\kappa(T)$ of Y211 polycrystals is larger than $\kappa_c(T)$ of Y–Ba–Cu–O bulk, so that the small magnitude of the $\kappa_c$ of nonBM sample is anomalous. Therefore, it is obvious that the discrepancy in the $\kappa_c(T)$ between both Er–Ba–Cu–O bulks cannot be explained by the size of the Er211 particles or the composition ratio (Er123/Er211); we speculate that the stacking faults at the $CuO_2$ planes brings about the small $\kappa_c(T)$ for nonBM sample.

Fig. 2 shows the $\kappa_{ab}(T)$ curves of Er–Ba–Cu–O(BM) bulk for different annealing temperature $T_{an}$ = 400 °C and 500 °C, respectively. It is noticed that the slope in the normal state becomes somewhat large in sample with $T_{an}$ = 400 °C. The oxygen vacancies decrease monotonically with lowering $T_{an}$, meaning that the heat transfer tends to be dominated by phonon-phonon interaction in the lower $T_{an}$ sample. Thus, $T_{an}$ dependence of the $\kappa_{ab}(T)$ is consistent with this picture.

Fig. 3 shows the temperature dependence of the *ab*-plane electrical resistivity, $\rho_{ab}$, for the same bulks shown in Fig. 2. The $T_c$ for the sample with $T_{an}$ = 400 °C and 500 °C are of 88.7 K and 89.4 K, respectively. The magnitude of the resistivity for the sample with $T_{an}$ = 400 °C is smaller than that for $T_{an}$ = 500 °C, which is consistent with the amount of the oxygen vacancies. Since both $\rho_{ab}(T)$ curves show the good *T*-linear behavior, we can estimate the thermal conductivity due to the charge carriers, $\kappa^{ch}(=LT/\rho_{ab})$, using the Wiedemann–Franz law, where *L* is the Lorenz number. As a result, the former $\kappa^{ch}$ and the latter $\kappa^{ch}$, respectively, are estimated to be of about 5.7 and 4.2 mW/cm K above 100 K; which are quantitatively consistent with the difference in the total $\kappa(=\kappa^{ph}+\kappa^{ch})$ for both samples, where $\kappa^{ph}$ is the phonon thermal conductivity. Consequently, it is found that the nature of the $\kappa_{ab}$, especially in the normal state, is affected sensitively by the oxygen deficiencies.

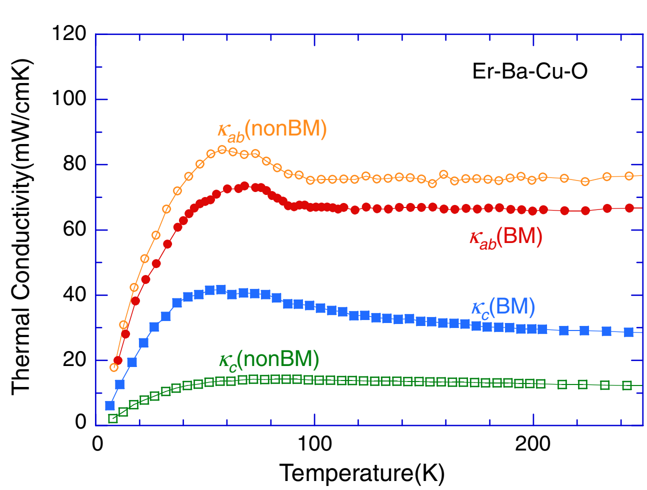


**Fig. 1.** The temperature dependence of the *ab*-plane and *c*-axis thermal conductivity, $\kappa_{ab}(T)$ and $\kappa_c(T)$, for Er–Ba–Cu–O bulk superconductors ($T_{an}$ = 450 °C). The closed and open symbols, respectively, represent the Er–Ba–Cu–O bulk with the ball-milled (BM) and nonBM Er211.

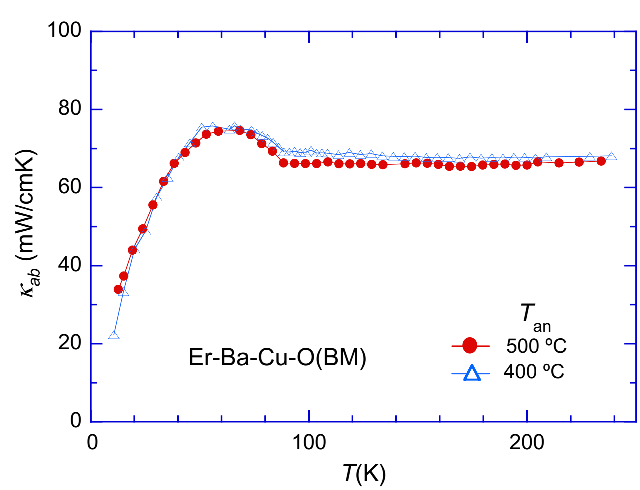


**Fig. 2.** The temperature dependence of the *ab*-plane thermal conductivity of Er–Ba–Cu–O bulk superconductors for $T_{an}$ = 400 °C and 500 °C.

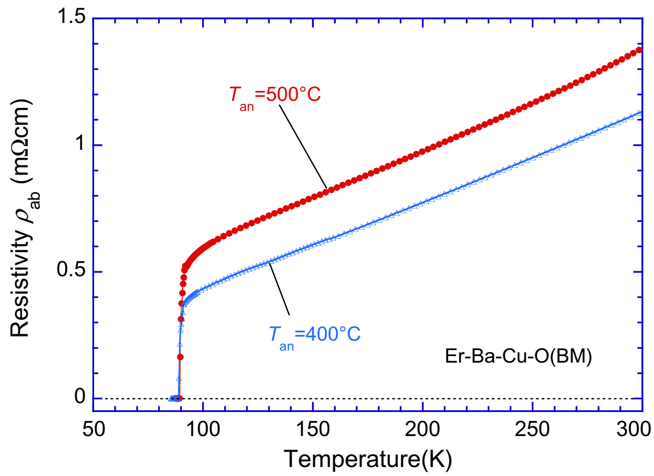


**Fig. 3.** The temperature dependence of the *ab*-plane electrical resistivity, $\rho_{ab}(T)$, of Er–Ba–Cu–O bulk superconductors for $T_{an}$ = 400 °C and 500 °C.

## 4. Summary

We have measured the temperature dependences of thermal conductivity in the *ab*-planes $\kappa_{ab}(T)$ and along the *c*-axis $\kappa_c(T)$ for Er–Ba–Cu–O bulk superconductors. We found that the $\kappa_{ab}(T)$ shows a quite moderate negative slope or *T*-independent behavior in the normal state. The absolute values of the $\kappa_{ab}$ are larger than those of the Dy–Ba–Cu–O bulks in the whole measuring temperatures, but are smaller than those of other RE–Ba–Cu–O bulks. The anisotropy of the thermal conductivity ($\kappa_{ab}/\kappa_c$) for Er–Ba–Cu–O bulks is estimated to be of about 2–6.

## Acknowledgements

This work was supported in part by the JGC-S Scholarship foundation (No. 1907) and a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan (No. 19560003) from JSPS, Japan.

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