Low-Thermal-Conductive DyBaCuO Bulk Superconductor for Current Lead Application

Hiroyuki Fujishiro, Manabu Ikebe, Hidekazu Teshima, and Hosei Hirano

***Abstract*—The thermal conductivity $\kappa(T)$, thermal diffusivity $\alpha(T)$ and thermal dilatation $dL(T)/L$ of the DyBaCuO bulk superconductor have been measured. The *ab*-plane κ of the bulk at 50 K is about one third of that of the YBaCuO bulk, and moreover, the superconducting characteristics (critical current density J_c and superconducting transition temperature T_c) compare favorably with those of the YBaCuO bulk. The current-voltage (*I-V*) characteristics of the current lead fabricated from DyBaCuO bulk and the durability against the thermal quenching are as good as those of the YBaCuO lead. The DyBaCuO bulk is a promising material for the power current lead use to be replaced for the YBaCuO bulk.**

***Index Terms*—DyBaCuO bulk, heat intrusion, low thermal conductivity, power current lead, thermal dilatation.**

I. INTRODUCTION

THE SUPERCONDUCTING current lead using the melt-textured REBaCuO superconducting bulk (RE = rare earth elements and Y) is one of the exemplary models for practical applications of high-T_c superconductors, in which both the low thermal conductivity κ and the high critical current density J_c are indispensable conditions. The REBaCuO bulk is a composite material, which consists of $REBa_2Cu_3O_y$ (RE123) superconducting matrix, RE_2BaCuO_5 (RE211) nonsuperconducting secondary phase, Ag and Pt metals. The temperature dependence of $\kappa(T)$ depends on the quality of the RE123 phase, the content, size and dispersion of the RE211 phase and Ag particles. For the RE = Y, Gd, Sm and Nd systems, the crystal growth method has been optimized to attain the higher J_c and trapped field B_T. The thermal properties such as $\kappa(T)$ and the thermal diffusivity $\alpha(T)$ were also reported for each system [1]–[3]. Recently, a higher B_T of 1.4–1.9 T at 77 K has been obtained for the large single domain DyBaCuO with 32–48 mm in diameters, far exceeding B_T of YBaCuO bulk [4]–[6]. This system has a merit of possible crystal growth in air. However, there is no detailed report for the thermal properties for the DyBaCuO bulk.

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In this paper, we study the thermal properties such as $\kappa(T)$, $\alpha(T)$ and the thermal dilatation $dL(T)/L$ of the DyBaCuO bulk in the *ab*-plane and along the *c*-axis. The *ab*-plane $\kappa(T)$ of the DyBaCuO bulk is fairly lower than that of the YBaCuO bulk. We fabricated the power current leads using DyBaCuO bulk and measured the current-voltage (*I-V*) characteristics and the durability against the heat cycles between 77 K and room temperature. As a result, the DyBaCuO bulk has proved to be a promising material for the power current lead application to be replaced for the YBCO bulk usually used.

II. EXPERIMENTAL PROCEDURE

A. Sample Preparation and Thermal Property Measurements

A highly *c*-axis oriented DyBaCuO bulk superconductor was prepared by a modified quench and melt growth (QMG) method at Nippon Steel Co., Ltd. [7]. The bulk was composed of $DyBa_2Cu_3O_y$ (Dy123) and Dy_2BaCuO_5 (Dy211) with a molar ratio of Dy123:Dy211 = 1.0:0.33 and 0.5 wt% Pt powder. The precursor disk was partially melted at 1150°C and then cooled down to 1040°C, keeping a temperature gradient between the top and bottom of the disk. A NdBaCuO or SmBaCuO seed crystal was attached to the top-center of the disk to promote highly oriented crystal growth. The bulk was slowly cooled down from 1040°C to 970°C. After the parallelepiped shaped specimens designed for along the *ab*-plane and *c*-axis measurements were cut from the grown disk, the specimens were heat treated at 450°C for 100 h in flowing oxygen to materialize the superconductivity.

The thermal conductivity $\kappa(T)$ was measured by a steady-state heat flow method and the thermal diffusivity $\alpha(T)$ measurement was performed by an arbitrary heating method under an identical experimental setup with the κ measurement [8]. The thermal dilatation $dL(T)/L = (L(300\,\mathrm{K}) - L(T))/L(300\,\mathrm{K})$ was measured by a strain gauge method, which was normalized to the length L at 300 K [1]. The electrical resistivity $\rho(T)$ was measured by a four terminal method. A Gifford-McMahon (GM) cycle helium refrigerator was used as a cryostat for the measurements between 10 and 300 K.

B. Design of Power Current Lead Using DyBaCuO Bulk

Two types of the current leads were fabricated and tested. Fig. 1 presents the photograph which shows a schematic view of the current leads; one is referred as "B-type" and the other as "1 K-type". For the "B-type" lead, a thin plate parallel to the *ab*-plane of the DyBaCuO bulk ($5 \times 0.8\ \mathrm{mm}^2$ in cross section and 40 mm in length) was used. In the "1 K-type" lead, an *I*-shaped DyBaCuO bar ($4 \times 4\ \mathrm{mm}^2$ in cross section and 58 mm in length) with length direction parallel to the *ab*-plane

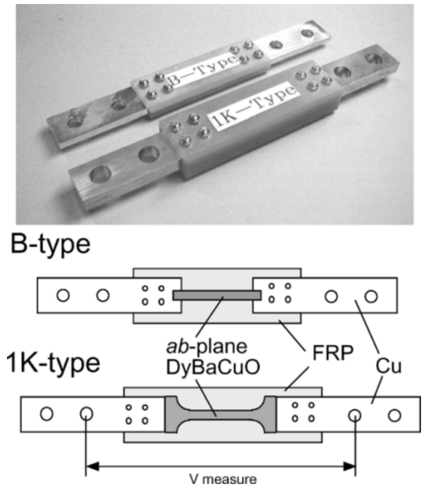

Fig. 1. Photograph (upper panel) and schematic view (lower panel) of the two types of power current leads fabricated by use of the ab-plane DyBaCuO bulk.

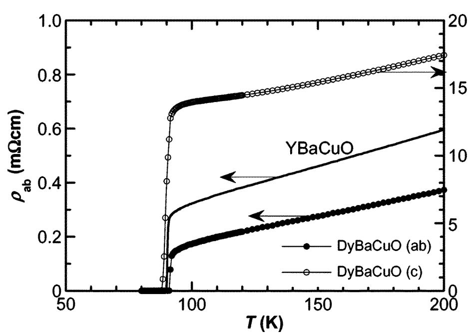

Fig. 2. The temperature dependence of the ab-plane and c-axis resistivity $\rho_{\mathrm{ab}}(T)$, $\rho_{\mathrm{c}}(T)$ of the DyBaCuO and YBaCuO bulks.

was used. The DyBaCuO bulk was connected with the Cu terminals and was covered with fiber reinforced plastics (FRPs). The current-voltage (*I-V*) characteristics were measured at 77 K under the magnetic field of ~0.5 T by attaching the Nd − Fe − B permanent magnet onto the lead. The sweep rate of the current was 12 A/s and 36 A/s for the "B-type" and "1 K-type", respectively. The endurance test against the heat cycle between 77 K and room temperature was performed by measuring the change of resistance between Cu terminals.

III. Results and Discussion

A. *Thermal Properties of* DyBaCuO *Bulk*

Fig. 2 shows the temperature dependence of the ab-plane and c-axis electrical resistivity $\rho_{\mathrm{ab}}(T)$, $\rho_{\mathrm{c}}(T)$ for the DyBaCuO bulk. For comparison, $\rho_{\mathrm{ab}}(T)$ of YBaCuO bulk with the same composition (Y123 : Y211 = 1.0 : 0.33, Pt = 0.5 wt%, without Ag metal) is also given. $\rho_{\mathrm{ab}}(T)$ of DyBaCuO bulk is 0.37 mΩcm at 200 K and is smaller than that of YBaCuO bulk, suggesting a good crystalline state of the $\mathrm{DyBa_2Cu_3O_y}$ bulk. T_{c} is 91.5 K and slightly higher than that of YBaCuO bulk. $\rho_{\mathrm{c}}(T)$ of the DyBaCuO bulk is about two orders of magnitude higher than $\rho_{\mathrm{ab}}(T)$.

Fig. 3 shows the temperature dependence of the ab-plane and c-axis thermal conductivity $\kappa_{\mathrm{ab}}(T)$, $\kappa_{\mathrm{c}}(T)$ for the DyBaCuO bulk, comparing with those of the YBaCuO bulk. $\kappa_{\mathrm{ab}}(T)$ of

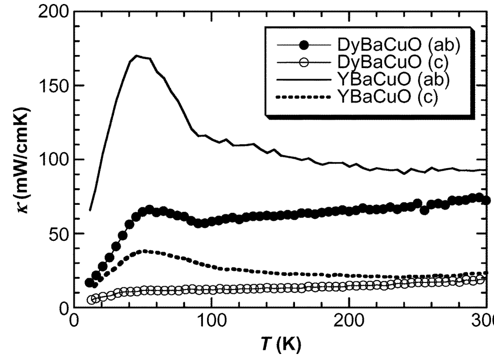

Fig. 3. The temperature dependence of the ab-plane and c-axis thermal conductivity $\kappa_{\mathrm{ab}}(T)$, $\kappa_{\mathrm{c}}(T)$ of the DyBaCuO bulk. For comparison, those of the YBaCuO bulk with the same composition are also shown.

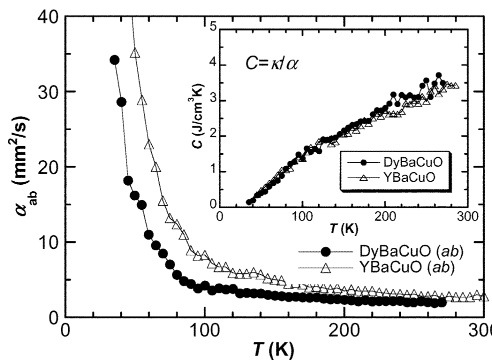

Fig. 4. The temperature dependence of the ab-plane thermal diffusivity $\alpha_{\mathrm{ab}}(T)$ of the DyBaCuO and YBaCuO bulks. The inset shows the specific heat $C(T)$ estimated using the relation $C(T) = \kappa_{\mathrm{ab}}(T)/\alpha_{\mathrm{ab}}(T)$.

both DyBaCuO and YBaCuO exhibits a broad peak below T_{c}, characteristic of the high T_{c} superconductors. It should be noticed that $\kappa_{\mathrm{ab}}(T)$ of the DyBaCuO bulk is fairly lower than that of the YBaCuO bulk; $\kappa_{\mathrm{ab}}(T)$ of DyBaCuO is about one half (at T_{c}) and one third (at 50 K) of that of the YBaCuO bulk. The magnitude of κ_{ab} of DyBaCuO bulk is as small as that of the SmBaCuO bulk [2]. It has been found that in the REBaCuO system with the light RE (LRE) element such as Sm and Nd, a part of the LRE ions is substituted for the Ba site and forms the $\mathrm{LRE_{1+y}Ba_{2-y}Cu_3O_z}$-type solid solution [9], resulting in the strong phonon scattering centers [2]. Since RE = Dy is not LRE element and the ionic radius of $\mathrm{Dy^{3+}}$ is small comparable with $\mathrm{Y^{3+}}$, the Dy ion has been believed to be the nonsubstituted one for the Ba site. From the thermal conductivity measurement, a sizable amount of the migration of Dy and Ba may take place or other powerful phonon scattering centers may be introduced.

Our previous κ data for sintered $\mathrm{DyBa_2Cu_3O_7}$ [10] suggested the existence of a strong phonon scattering mechanism other than point defect type, whose scattering strength is nearly independent of temperature. In order to clarify the relevant physical mechanisms of low thermal conductivity, detailed studies are in progress. The c-axis thermal conductivity $\kappa_{\mathrm{c}}(T)$ of the DyBaCuO bulk is also fairly smaller than that of the YBaCuO bulk with no characteristic broad peak at low temperature.

Fig. 4 presents the ab-plane thermal diffusivity $\alpha_{\mathrm{ab}}(T)$ of DyBaCuO and YBaCuO bulks as a function of T. The inset shows the specific heat $C(T)$ estimated using the relation $C(T) = \kappa_{\mathrm{ab}}(T)/\alpha_{\mathrm{ab}}(T)$. In the normal state ($T > T_{\mathrm{c}}$),

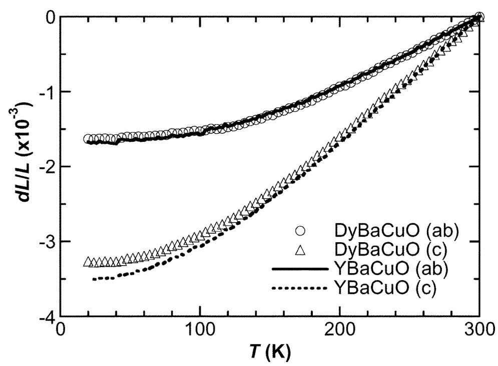

Fig. 5. The temperature dependence of the thermal dilatation $dL(T)/L$ of the DyBaCuO bulk in the ab-plane and along the c-axis. For comparison, those of the YBaCuO bulk with the same composition are also shown.

$\alpha_{\rm ab}(T)$ of both samples increases slightly with decreasing temperature. Below $T_{\rm c}$, $\alpha_{\rm ab}(T)$ increases more and more rapidly with decreasing temperature. The absolute value of $\alpha_{\rm ab}$ of the DyBaCuO bulk is smaller than that of the YBaCuO bulk. These results are reasonable because the specific heat $C(T)$ for the REBaCuO bulk should hardly depend on the species of RE ions [11], [12].

Fig. 5 shows the temperature dependence of the thermal dilatation $dL(T)/L$ of the DyBaCuO bulk in the ab-plane and along the c-axis compared with that of YBaCuO bulk. For both in the ab-plane and along the c-axis, $dL(T)/L$ decreases (the absolute value $|dL/L|$ increases) with decreasing temperature T, showing a tendency for saturation at low temperatures. The c-axis $|dL(T)/L|$ is nearly twice as large as that of ab-plane. It should be noticed that $dL(T)/L$ of the DyBaCuO bulk is similar to that of the YBaCuO bulk for both ab-plane and c-axis. The $dL(T)/L$ data are a valuable physical quantity in the case of the current lead design.

B. Calculation of Heat Intrusion Through the Current Lead

The heat intrusion $Q_{\rm C}$ through the current lead was calculated using the $\kappa_{\rm ab}(T)$ data shown in Fig. 3. As the current lead consists of the bulk and the FRP support, the heat flows in parallel through both the bulk and the FRP. The $Q_{\rm C}$ value of the current lead in the area between the temperatures, $T_{\rm H}$ and $T_{\rm L}$, is given by

$$\begin{aligned} Q_{\rm C} &= Q_{\rm bulk} + Q_{\rm FRP} \\ &= \frac{A_{\rm bulk}}{L}\int_{T_{\rm L}}^{T_{\rm H}} \kappa_{\rm bulk}(T)dT + \frac{A_{\rm FRP}}{L}\int_{T_{\rm L}}^{T_{\rm H}} \kappa_{\rm FRP}(T)dT \end{aligned} \tag{1}$$

where L is the length of the lead, and $A_{\rm bulk}$ and $A_{\rm FRP}$ are the cross sections of the bulk and FRP, respectively. The $\kappa_{\rm FRP}(T)$ data from the literature were used. Table I shows the results of the $Q_{\rm C}$ values in cases of the [$T_{\rm H}$ = 77 K, $T_{\rm L}$ = 4 K] and [$T_{\rm H}$ = 40 K, $T_{\rm L}$ = 4 K] for both the DyBaCuO and YBaCuO bulks, respectively. $Q_{\rm bulk}$ in (1) is far larger than $Q_{\rm FRP}$. The heat intrusion $Q_{\rm C}$ using DyBaCuO bulk decreases to about a half of that of the YBaCuO bulk current lead.

TABLE I
ESTIMATED $Q_{\rm C}$ VALUES FOR THE CURRENT LEADS USING DyBaCuO AND YBaCuO BULKS

	B-type		1K-type	
$T_{\rm H}$, $T_{\rm L}$ condition	DyBaCuO	YBaCuO	DyBaCuO	YBaCuO
$T_{\rm H}$=77 K, $T_{\rm L}$=4 K	0.07 W	0.15 W	0.14 W	0.30 W
$T_{\rm H}$=40 K, $T_{\rm L}$=4 K	0.03 W	0.06 W	0.06 W	0.12 W

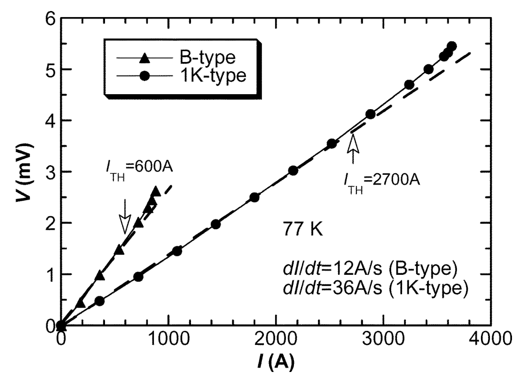

Fig. 6. The *I-V* characteristics of two types of current leads using the DyBaCuO bulk at 77 K. The additional voltage generation takes place above the threshold $I_{\rm TH}$ due to the excess current.

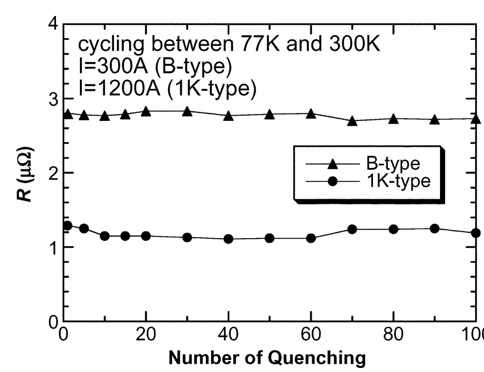

Fig. 7. The results of the durability against the 100 heat cycles.

C. Characteristics of DyBaCuO Current Lead

Fig. 6 presents the current-voltage (*I-V*) characteristics for both types of current leads at 77 K. For the low current region, the *I-V* characteristics are linear. In current region higher than the threshold value $I_{\rm TH}$, the *I-V* curve deviates from the linear line and the additional voltage is generated due to the excess current above the critical current $I_{\rm c}$ of the DyBaCuO bulk. The $I_{\rm TH}$ value is roughly 600$\sim$1000 A for "B-type" and 2700$\sim$3600 A for "1 K-type", respectively. These results are similar to the current lead using the YBaCuO bulk [13].

Fig. 7 shows the results of the endurance test against the heat cycle. The current leads were immersed in liquid N_2 and then were warmed in air to the room temperature. This thermal cycle was repeated by 100 times. The current of 300 A for "B-type" and 1200 A for "1 K-type" was flown through the lead in liquid N_2 for every 10 cycles and the resistance R between the voltage terminals are given in Fig. 7. It was found that the resistance does not change after the 100 times heat cycling and no burning-out of the lead was observed. The durability of the lead using the DyBaCuO bulk shows a high performance similar to that using the YBaCuO bulk [13].

IV. Summary

1) The thermal conductivity $\kappa(T)$, thermal diffusivity $\alpha(T)$ and thermal dilatation $dL(T)/L$ of the DyBaCuO bulk superconductor have been measured in the *ab*-plane and along the *c*-axis. The *ab*-plane $\kappa(T)$ at 50 K is very small and is about one third of that of the YBaCuO bulk. The superconducting characteristics compare rather favorably with those for YBCO bulk. These results strongly suggest that the DyBaCuO bulk is a promising material for the power current lead application to be replaced for the YBCO bulk.
2) The power current leads were fabricated using the DyBaCuO bulk. The heat intrusion Q_C through the lead using DyBaCuO bulk decreased to about a half of that using YBaCuO bulk. The current-voltage (*I-V*) characteristics and the durability against the thermal quenching for the current lead fabricated by DyBaCuO showed the desirable behavior. The power current lead using DyBaCuO bulk superconductor provides an excellent electrical properties and the mechanical strength similarly to those of the YBaCuO lead.

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