Thermal Conductivity and Thermal Dilatation of Commercial BSCCO (DI-BSCCO) Tapes

Tomoyuki Naito, Hiroyuki Fujishiro, and Yuichi Yamada

***Abstract*—We have measured the thermal conductivity, $\kappa(T)$, and thermal dilatation, $\delta L(T)/L(300\ \mathrm{K})$, as a function of the temperature for four types of commercial $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_{10+x}$ (Bi2223) tapes sheathed with silver-alloy (DI-BSCCO). $\kappa(T)$ of three Bi2223/Ag-alloy tapes [Type H, Type HT, and Type AC] shows a similar temperature dependence, but the absolute value of the $\kappa(T)$ depends on the structure and volume ratio of sheath part. The sheath material of types H and AC is a silver-alloy and that of type HT consists of both silver-alloy and stainless steel tapes. Type AC has the twisted Bi2223 filaments. On the other hand, $\kappa(T)$ of the Bi2223/Ag-5.4wt%Au-alloy tape [Type G] shows very low value and decreases monotonically with decreasing temperature. Near 77 K, the absolute values of the type H and type G tapes were about 260 $\mathrm{W\ m^{-1}\ K^{-1}}$ and 80 $\mathrm{W\ m^{-1}\ K^{-1}}$, respectively. $\delta L(T)/L(300\ \mathrm{K})$ of four tapes decreases with decreasing temperature, and approaches $-0.31 \sim -0.38\%$ below 25 K for all the tapes.**

***Index Terms*—DI-BSCCO, thermal conductivity, thermal dilatation.**

I. Introduction

THE $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_{10+x}$ (Bi2223) tapes sheathed with silver-based alloy, Bi2223/Ag-alloy, have been developed by many researchers and companies. Recently, Sumitomo Electric Industries, Ltd. (SEI) developed a new sintering technique with the controlled overpressure (CT-OP) [1], which enables us to fabricate the Bi2223/Ag-alloy tape including very small amount of voids and nonsuperconducting region and having a high Young's modulus in comparison with the conventional Bi2223/Ag-alloy tapes. Using this technique, SEI succeeded in making a Bi2223/Ag-alloy tape with high critical current, I_c, over 200 A at 77 K and under the self-field [2]. This value gives us the possibility that the superconducting applications such as high-field coil magnet, power cable are practicably operated at 77 K. Since the Bi2223/Ag-alloy tapes made by CT-OP technique surpass other tapes in all properties, SEI named them Dynamically Innovative BSCCO (DI-BSCCO).

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T. Naito and H. Fujishiro are with the Faculty of Engineering, Iwate University, Morioka 020-8551, Japan (e-mail: tnaito@iwate-u.ac.jp; fujishiro@iwate-u.ac.jp).

Y. Yamada is with the Superconductivity and Energy Technology Department and Electric Power and Energy Research Laboratories, Sumitomo Electric Industries, Ltd., Osaka 554-0024, Japan (e-mail: yamada-yuichi@sei.co.jp).

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When the superconducting materials are used in the practical devices, we need to estimate correctly the amount of heat intrusion through them [3]. The heat intrusion, Q_{int}, in the materials between a low and high temperature sides, T_{L} and T_{H}, is in general given by

$$Q_{\mathrm{int}} = \frac{S}{l}\int_{T_{\mathrm{L}}}^{T_{\mathrm{H}}} \kappa(T)\,dT,$$

where κ is the thermal conductivity, l the length and S the cross section of the material. In the case of the Bi2223/Ag-alloy tapes, the absolute value and temperature dependence of κ are mainly dominated by the sheath material, the volume ratio of sheath material to the Bi2223 and fabrication process [3]–[5]. However, $\kappa(T)$ of DI-BSCCO has not been measured yet. On the other hand, the thermal dilatation, $\delta L/L$, is also the important physical property, because the change in the length of the tape would give itself a mechanical stress which suppresses the superconducting properties. In this paper, we report the temperature dependence of the thermal conductivity, $\kappa(T)$, and thermal dilatation, $\delta L(T)/L(300\ \mathrm{K})$, for four types of DI-BSCCO tapes.

II. Sample

DI-BSCCO tapes were fabricated by the powder in tube (PIT) method with the CT-OP sintering technique. The details of the sample preparation were described elsewhere [1]. Table I summarizes the specifications of four types of DI-BSCCO tapes (types H, HT, G, and AC) investigated in this study. Type H, whose sheath is a silver-alloy, is a standard tape. The silver-alloy consists of the silver and a small amount of other metal element. In order to achieve a high yield stress, type HT was prepared, in which the type H tape was laminated from both surfaces by the stainless steel (SUS) tapes 0.02 mm in thickness. The sheath material of type G is an Ag-5.4wt%Au alloy. Type AC is designed for AC applications, in which the twisted Bi2223 filaments are sheathed by the silver-alloy.

III. Experimental Procedure

Thermal conductivity, $\kappa(T)$, along the tape surface, i.e. the ab-planes of the Bi2223 filaments, was measured by a steady-state heat flow method [6]. The experimental setup is schematically shown in the inset of Fig. 2. One end of the tape was soldered to the copper-block (sample stage). We use a small metal chip resistor of 1 kΩ as a heater, which was adhered to the other end of the tape by GE7031 varnish. κ is obtained by the relation,

$$\kappa = \frac{Q}{\Delta T}\cdot\frac{l}{S},$$

TABLE I
SPECIFICATIONS OF THE DI-BSCCO TAPES

Type	sheath material	T_c (K)	cross section (mm^2)	width (w) (mm)	thickness (t) (mm)
H	Ag alloy	110.8	0.935	4.25	0.22
HT	Ag alloy + SUS	111.0	1.100	4.40	0.31*
G	Ag-5.4wt%Au	111.0	0.994	4.14	0.24
AC	Ag alloy	110.8	0.440	2.20	0.20

* including the thickness of SUS parts (0.02 mm × 2) and solder layers (N.A.).

where Q is applied heat flow, ΔT is temperature difference and l is the distance between two chromel-constantan thermocouples, and S is the cross sectional area of sample. ΔT was maintained to be 0.5–0.8 K by controlling the heater power. Thermal dilatation normalized by the sample length, L, at 300 K, $\delta L(T)/L(300\text{ K}) = (L(T) - L(300\text{ K}))/L(300\text{ K})$, was measured by a strain-gauge method using a commercial strain-gauge (CFLA-1-350-11 [the gauge length is 1 mm, the gauge resistance is 350 Ω, and the gauge factor is 2.09]; Tokyo Sokki Kenkyujo Co., Ltd.). Electrical resistivity, ρ, was measured by a four-probe method with a typical current density of about 3 A/cm^2. The temperature of sample stage was controlled between 5 and 300 K using a Gifford-McMahon cycle helium refrigerator. To minimize a radiation loss, κ was measured below 250 K. $\delta L(T)/L(300\text{ K})$ was measured above 10 K because of the sensitivity of strain gauge.

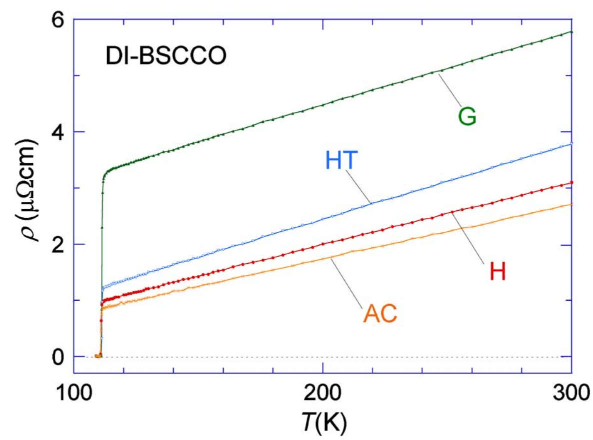

Fig. 1. Temperature dependence of the electrical resistivity for four types of DI-BSCCO tapes. The sheath material is different; Ag-alloy (types H and AC), Ag-alloy + stainless steel (type HT), and Ag-5.4wt%Au-alloy (type G).

IV. RESULTS AND DISCUSSION

A. Electrical Resistivity

Fig. 1 shows the temperature dependence of the electrical resistivity, $\rho(T)$, for various DI-BSCCO tapes. The critical temperature, T_c, is about 111 K for all the samples, indicating good quality of the superconducting part of Bi2223 filaments. All the $\rho(T)$ curves show a good T-linear dependence in the normal state. In this regime, the absolute value of $\rho(T)$ of the metal sheaths are rather smaller than that of Bi2223 filaments, therefore the applied current mainly flows through the part of the metal sheath; for instance, the ρ value for the Bi2223 polycrystal was reported to be about 900 $\mu\Omega\text{cm}$ at 295 K [6] and that for pure silver 1.6 $\mu\Omega\text{cm}$ at room temperature [7]. The absolute value of $\rho(T)$ for type G is rather larger than those for other three types, because the sheath material of type G is the solid solution of Ag-Au alloy (Ag-5.4wt%Au alloy). On the other hand, the ρ value for type AC is slightly smaller than that for type H, although both sheath materials are the same. These results originate from the fact that type AC contains twisted Bi2223 filaments with large ρ and the volume ratio of the low-resistive sheath material to the Bi2223 filament of the type AC is larger than that of the type H.

B. Thermal Conductivity

Fig. 2 shows the temperature dependence of the thermal conductivity, $\kappa(T)$, for various DI-BSCCO tapes. $\kappa(T)$ of type H decreases quite slightly with decreasing temperature from 250 K to 100 K. It increases moderately between 100 K and 60 K, starts to increase rapidly below 60 K, and takes a peak of 780 $\text{W m}^{-1}\text{ K}^{-1}$ around 17 K. The steep increase and peak structure is often observed in $\kappa(T)$ of a high-purity silver [9], which originates from the fact that the mean free path of the electrons becomes large in the low temperatures. The behavior of $\kappa(T)$ for type HT is basically similar to that of type H, but the absolute value of for type HT is about 20%–25% smaller than that for type H. Assuming that the thickness of the "type H" tape in the type HT is the same as that of the type H tape measured in this study, the ratio of the cross section between a couple of SUS with solder layers and the whole tape is estimated to be 0.29:1. Therefore, $\kappa(T)$ of type HT should be smaller about 29% than that of type H, if the applied heat thoroughly flows through the part of Ag-alloy. SUS is a poor heat conductor compared with Ag. For instance, the absolute values of κ of a standard sample of the austenitic stainless steel (SRM1460) provided by NIST (the National Institute of Standards and Technology) are about 12 $\text{W m}^{-1}\text{ K}^{-1}$ at 200 K and 1.5 $\text{W m}^{-1}\text{ K}^{-1}$ at 20 K [8]. On the other hand, those of pure Ag are approximately 600 $\text{W m}^{-1}\text{ K}^{-1}$ at 200 K and 20000 $\text{W m}^{-1}\text{ K}^{-1}$ at 20 K [9]. Therefore, we can consider that the most of applied heat flows through the part of Ag-alloy sheath also for type HT, giving rise to the reduction of $\kappa(T)$. $\kappa(T)$ of type G decreases monotonically with decreasing temperature. The absolute value of κ of type G near 77 K is about one third of that of type H. No peak and a small value in the $\kappa(T)$ for type G is often observed in the low-purity Ag-Au alloys [9], which originates from the fact that the impurities scatter the electrons. The similar $\kappa(T)$'s have been observed in the Bi2223 tapes sheathed with other metal alloy [3]–[5]. $\kappa(T)$ of type AC behaves similarly to that of types H and HT, but the peak value of type AC near 10 K is extremely larger than that for other two types. This large peak suggests that the volume ratio of sheath material to the Bi2223 is large in type

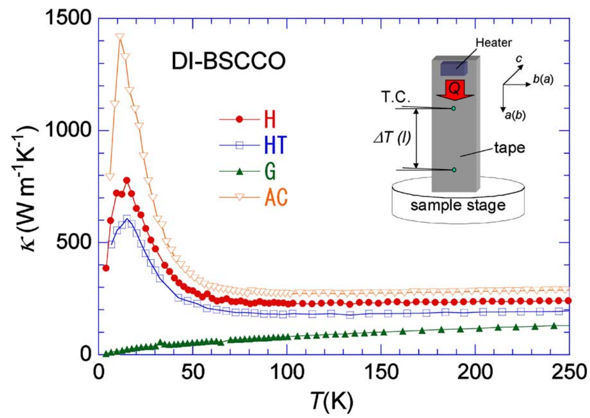

Fig. 2. Temperature dependence of the thermal conductivity, $\kappa(T)$, for four types of DI-BSCCO tapes. The sheath material is different; Ag-alloy (types H and AC), Ag-alloy + stainless steel (type HT), and Ag-5.4wt%Au-alloy (type G). The experimental setup is schematically illustrated in the inset, where the coordinate axes represent the crystallographic axes of Bi2223. T.C. is thermocouple. Q, ΔT and l are notated in the text.

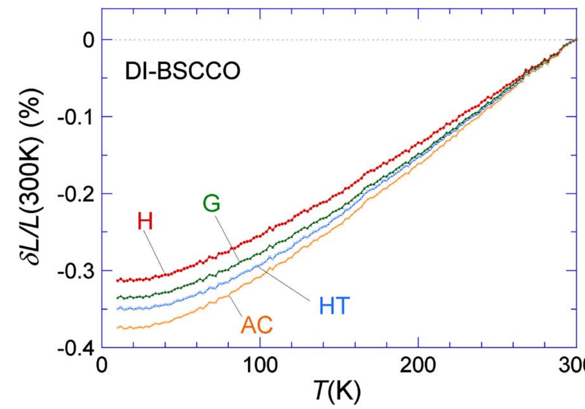

Fig. 3. Temperature dependence of the thermal dilatation, $\delta L/dL(300\ \mathrm{K})$, for four types of DI-BSCCO tapes. The sheath material is different; Ag-alloy (types H and AC), Ag-alloy + stainless steel (type HT), and Ag-5.4wt%Au-alloy (type G).

AC. Finally, we note that no anomaly is observed at T_c in any of the samples.

In a conducting solid, the measured thermal conductivity comprises both contributions due to phonons and electrons, $\kappa_{\rm ph}$ and $\kappa_{\rm el}$. The $\kappa_{\rm el}$ component can be estimated from the electrical resistivity, ρ, using the Wiedemann–Franz law, $\kappa_{\rm el} = L_0 T/\rho$, where $L_0 (= 2.45 \times 10^{-8}\ \mathrm{W}\ \Omega^{-1}\ \mathrm{K}^{-1})$ is the Lorenz number. Since the $\rho(T)$ curves show the good T-linear dependence above T_c, as found in Fig. 1, the $\kappa_{\rm el}$'s are expected to be T-independent. The obtained values of $\kappa_{\rm el}$ at 150 K for each sample are about 244 (type H), 198 (type HT), 110 (type G), and 282 $\mathrm{W\ m^{-1}\ K^{-1}}$ (type AC), respectively. These values are comparable with the measured κ values in the normal state. On the other hand, the κ value of the sintered Bi2223 polycrystal was reported to be about 3.3 $\mathrm{W\ m^{-1}\ K^{-1}}$ at 150 K [6]. Therefore, the contribution of the Bi2223 filament to the heat transport is negligibly small and the most of the applied heat is carried by electrons in the metal sheath.

C. Thermal Dilatation

Fig. 3 shows the temperature dependence of the thermal dilatation $\delta L(T)/L(300\ \mathrm{K})$ for various DI-BSCCO tapes. $\delta L(T)/L(300\ \mathrm{K})$ of all the samples shows a similar temperature dependence; from 300 K to 25 K, the $\delta L(T)/L(300\ \mathrm{K})$ decreases monotonically with decreasing temperature, and shows almost constant value of $-0.31 \sim -0.38\%$ below 25 K. Recently, Weiss *et al.* reported that the thermal dilatation of types H and HT at 5 K are approximately -0.27% and -0.3%, respectively [5], which are about 10% smaller than the present results. However, we cannot discuss the discrepancy, because they did not described the measuring method and accuracy.

V. Summary

We have measured the thermal conductivity, $\kappa(T)$, and thermal dilatation, $\delta L(T)/L(300\ \mathrm{K})$, as a function of the temperature for four types of DI-BSCCO tapes. The $\kappa(T)$ of both Bi2223/Ag-alloy (type H) and Bi2223/Ag-alloy laminated by stainless steel (type HT) show a similar temperature dependence, but the absolute values of κ of type HT is approximately 20%–25% smaller than that of type H, which indicates that the $\kappa(T)$ of type HT is dominated by the sheath material with low-thermal-conductive SUS. For the Bi2223/Ag-5.4wt%Au-alloy (type G), the $\kappa(T)$ decreases monotonically with decreasing temperature and its magnitude is rather smaller than that of type H. The $\kappa(T)$ of type AC shows a very large peak near 10 K, which might originate from the larger volume ratio of Ag compared with that of type H. The $\delta L(T)/L(300\ \mathrm{K})$ shows a similar temperature dependence for all the samples. It reaches nearly constant value of $-0.31 \sim -0.38\%$ below 25 K.

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