Anisotropic Thermal Conductivity of Silver Sheathed Bi2223 Superconducting Tape

Tomoyuki Naito, Hiroyuki Fujishiro, and Jun Fujikami

***Abstract*—Anisotropic thermal conductivity, $\kappa(T)$, of a silver sheathed Bi2223 (Bi2223/Ag) tape was determined for three typical directions; the length (l), width (w), and thickness (t). $\kappa(T)$ of the tape along the l-direction was measured directly and those along the w- and t-directions were estimated by measuring stacked samples in which several Bi2223/Ag tapes were soldered. $\kappa(T)$ of the tape along the l- and w-directions was 250 $\mathrm{W\ m^{-1}\ K^{-1}}$ at 77 K and almost coincided with each other. On the other hand, $\kappa(T)$ of the tape along the t-direction was about one order of magnitude smaller than those along other directions. The measured $\kappa(T)$ curves were analysed using an equivalent heat current circuit. Results show that the applied heat flows through the Ag parts for three directions. The amount of the Ag parts being in the route of the heat current depends on the direction.**

***Index Terms*—Anisotropy, equivalent heat current circuit, silver sheathed Bi2223 tape, thermal conductivity.**

I. Introduction

A SILVER sheathed Bi2223 (Bi2223/Ag) superconducting tape has been developed to achieve a long length cable with higher critical current density J_c. Recently, a Bi2223/Ag tape with high critical current, I_c, over 200 A at 77 K in the self-field was reported [1], [2], which gives us an opportunity to use the tape practically in power applications such as cables and high-field coil magnets. In the applications, it is important to estimate the thermal stability. We can calculate the amount of the heat intrusion and the heat exhaust through the tape, Q_t, using the thermal conductivity, $\kappa(T)$, by the following relation,

$$Q_{\rm t} = \frac{S}{L}\int_{T_1}^{T_2} \kappa(T)dT.$$

Here, S and L are the cross section and the length of the tape and T_1 and T_2 are the temperatures at both sides of the tape. In a winding coil, the heat might flow both along the length direction of the tape and along the radial direction of the coil, which is perpendicular to the thickness direction of the tape. We measured the anisotropic thermal resistance, $R(T)$, of a double-pancake coil using Bi2223/Ag tape and pointed out that the $\kappa(T)$ value of the tape along the thickness direction is important to analyse precisely the thermal transport along the radial direction [3]. However, $\kappa(T)$ of the Bi2223/Ag tapes have been usually measured only along the length direction [4]–[6], because the thickness of the tape is too thin to measure $\kappa(T)$ by a steady-state heat flow method.

In this paper, we measured and estimated the thermal conductivity of the Bi2223/Ag tape along three directions, the length, width and thickness. $\kappa(T)$ along the length direction was measured using a single tape, and those along the width and thickness directions were estimated using stacked bundles which consisted of several Bi2223/Ag tapes. We discuss the anisotropic heat flow in the Bi2223/Ag tape using an equivalent heat current circuit.

Fig. 1. Photograph of the cross section of the Bi2223/Ag tape. (White region) Ag parts and (black region) Bi2223 filaments.

II. Experimental Details

A. Sample Preparation

Bi2223/Ag tapes were 'Type H' tapes of DI-BSCCO family produced at Sumitomo Electric Industries, Ltd. by the powder in tube (PIT) method with the controlled overpressure (CT-OP) sintering technique [7]. The details of the fabrication process have been described elsewhere [7]. Fig. 1 shows a photograph of the cross section of the Bi2223/Ag tape. The white region represents the Ag sheath and the black one, the Bi2223 filaments. The "Ag-ratio" defined by $V_{\rm Ag}/V_{\rm Bi2223}$ was estimated to be about 1.8 from the photograph, where $V_{\rm Ag}$ and $V_{\rm Bi2223}$ were the volume of the Ag sheath and Bi2223 filaments, respectively.

$\kappa(T)$ of the Bi2223/Ag tape was determined along three typical directions, the length (l), width (w) and thickness (t), in the following. As described in Fig. 2(a), $\kappa(T)$ along the l-direction was measured directly using a single Bi2223/Ag tape, which was abbreviated as the l-sample. To estimate $\kappa(T)$ of the tape along the w- and t-directions, two stacked bundles were prepared by joining several Bi2223/Ag tapes using a commercial solder (LFM-48), as described in Fig. 2(b) and (c), which were named w- and t-sample, respectively. The dimensions of the samples are summarized in Table I.

B. Method of Thermal Conductivity Measurement

Thermal conductivity, $\kappa(T)$, of each sample was measured by a steady-state heat flow method. One end of the sample was soldered to a copper-block as a heat sink. A small metal chip

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TABLE I
SPECIFICATIONS OF THE SAMPLES

Sample name	distance between the thermocouples L (mm)	cross section S (mm^2)	width (mm)	thickness (mm)
l-sample	10.30	0.935	4.25	0.220
w-sample	8.40	8.20	4.10	2.00
t-sample	6.50	8.60	4.30	2.00

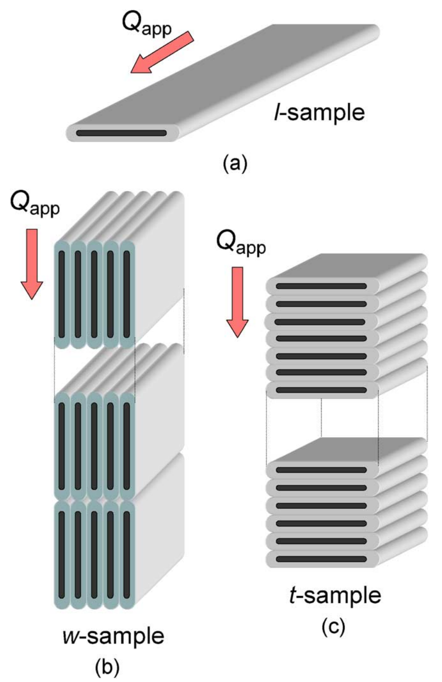

Fig. 2. Schematic illustration of (a) the single Bi2223/Ag tape for the measurement of the thermal conductivity $\kappa(T)$ along the length direction (l-sample) and the stacked bundles for the estimation of $\kappa(T)$ of the tape (b) along the width (w-sample) and (c) along the thickness direction (t-sample).

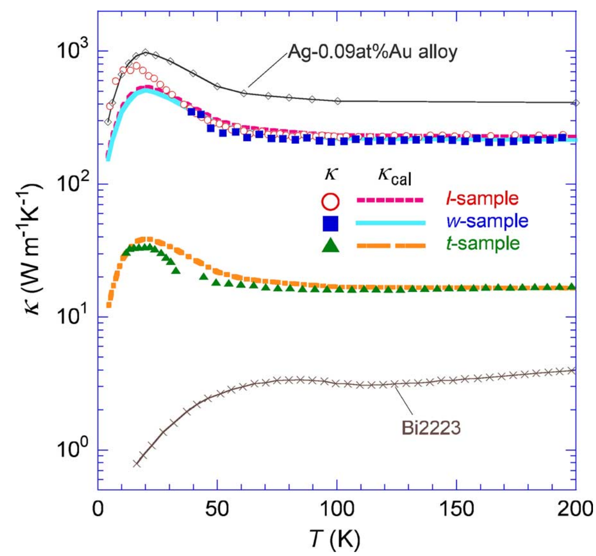

Fig. 3. Temperature dependence of the thermal conductivity $\kappa(T)$ for the length l, width w, and thickness t samples. The thick lines represent the calculated thermal conductivity $\kappa_{\mathrm{cal}}(T)$ (see text). The reported $\kappa(T)$ curves of Ag-0.09at%Au alloy [8] and Bi2223 polycrystal [9] are also plotted.

resistor (5 kΩ) was adhered to the other end of the sample as a heater using GE7031 varnish. κ is given as

$$\kappa = \frac{Q_{\mathrm{app}}}{\Delta T} \cdot \frac{L}{S}$$

where Q_{app} is the applied heat flow, ΔT the temperature difference and L the distance between the two thermocouples, and S is the cross section of the sample. ΔT was measured using two chromel-constantan thermocouples (76 μm in diameter) and was maintained at about 0.5–0.7 K by controlling the electric current applied to the chip resistor. The temperature of the sample stage was controlled using a Gifford-McMahon cycle helium refrigerator and 30 W heater. To eliminate the radiation loss, κ was measured below 200 K.

III. RESULTS

Fig. 3 presents the temperature dependence of the thermal conductivity, $\kappa(T)$, of three samples. $\kappa(T)$ of the l-sample slightly decreases with decreasing temperature, begins to increase below 60 K, and becomes maximum of about 800 W m^{-1} K^{-1} around 18 K, which is similar to $\kappa(T)$ of Bi2223/Ag tape reported previously [4]–[6]. $\kappa(T)$ of the w-sample almost coincides with that of the l-sample. For the w-sample, $\kappa(T)$ could not be measured below 40 K because of the limit of the heater power. The temperature dependence of $\kappa(T)$ of the t-sample is similar to that of other two samples. However the absolute value of $\kappa(T)$ of the t-sample is about one order of magnitude smaller than that of other samples. The thickness of the solder layer between the tapes is found to be extremely thin from the photograph (not shown here) and the $\kappa(T)$ value of the solder (LFM-48) [4] is rather larger than that of the t-sample. Therefore, the small $\kappa(T)$ value of the t-sample does not originate from the solder layers.

IV. DISCUSSION

As described in Fig. 1, the Bi2223 filaments distribute separately in the Ag sheath. The path of the heat current is rather complicated. We simply assume that the applied heat flows through both Ag and Bi2223 parts in parallel and suggest a simple model, in which all the Bi2223 filaments were virtually collected at the center of the tape in the cross section as shown in Fig. 4(a). The dimensions of the tape and the Bi2223 region along each direction were defined in the figure. The equivalent heat current circuits for the l-sample and both w- and t-samples are represented in Fig. 4(b) and (c), respectively. Here, R_{tape}, R_{Ag} and R_{Bi2223} are the thermal resistances of the whole tape, the Ag region and the Bi2223 filaments, respectively; R is given by $\kappa^{-1} \times (L/S)$. In general, the absolute value of $\kappa(T)$ of Bi2223 is about two orders of magnitude smaller than that of high-purity Ag, as shown in Fig. 3. The purity of the Ag sheath in the Type H tape was estimated to be about 99.9% from the $\kappa(T)$ measurement [4]. In this study, we use the reported $\kappa(T)$

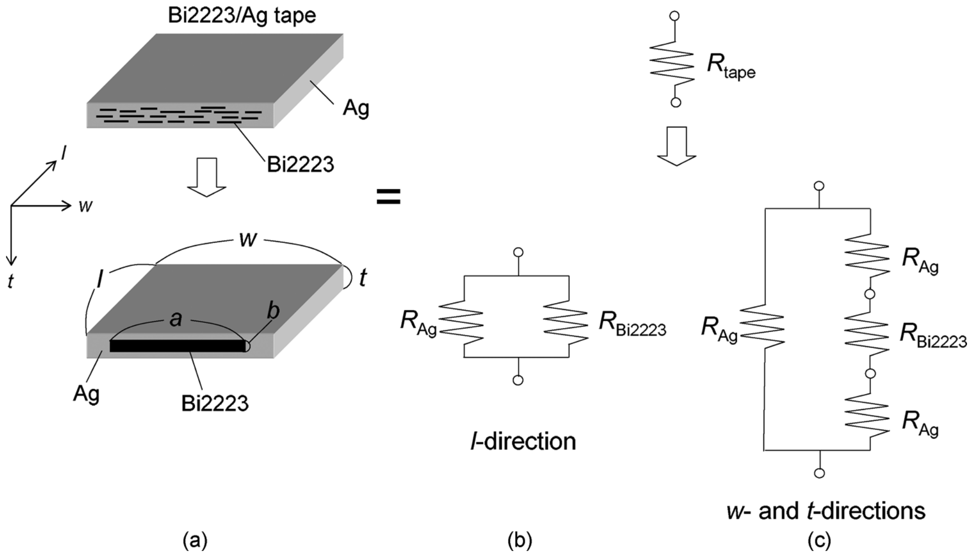

Fig. 4. (a) Schematic image of a model for the equivalent heat current circuit. The dimensions of the tape and the virtually collected Bi2223 region are illustrated. The equivalent heat current circuit for (b) the l-direction and (c) both w- and t-directions. $R_{\rm tape}$, $R_{\rm Ag}$, and $R_{\rm Bi2223}$ are the thermal resistances of the whole tape, the Ag region, and the Bi2223 filaments, respectively.

of Ag-0.09at%Au alloy [8] as $\kappa_{\rm Ag}(T)$. The $\kappa(T)$ value of the polycrystalline Bi2223 [9] is used as $\kappa_{\rm Bi2223}(T)$, because $\kappa(T)$ of Bi2223 single crystal has not been reported. Consequently, the heat current path including Bi2223 in series can be ignored because of $R_{2223} \gg R_{\rm Ag}$. Thermal conductivity along the l-direction, $\kappa_{\rm cal}^{(l)}(T)$, can be calculated by the following relation,

$$\kappa_{\rm cal}^{(l)}(T) = \kappa_{\rm Ag}(T) \times \left(1 - \frac{ab}{wt}\right).$$

In Fig. 3, the calculated $\kappa_{\rm cal}^{(l)}(T)$ is also presented. $\kappa(T)$ of the l-sample is well reproduced by $\kappa_{\rm cal}^{(l)}(T)$ for $(ab/wt) = 0.45$, except for around the peak structure at low temperature. The (ab/wt) value is the same as the filling factor of the superconductor, $f_{\rm sc}$, which is defined by the volume ratio of Bi2223 filaments to the whole tape and is roughly estimated to be 0.36, because Ag-ratio ($V_{\rm Ag}/V_{\rm Bi2223}$) was 1.8. The slight difference in $f_{\rm sc}$ suggests the small amount of Ag, about 15% of total Ag parts, does not contribute to the thermal transport. This might originate from the complicated heat path in the core region. $\kappa_{\rm cal}^{(w)}(T)$ of the tape along the w-direction and $\kappa_{\rm cal}^{(t)}(T)$ along the t-direction, respectively, are given by

$$\kappa_{\rm cal}^{(w)}(T) = \kappa_{\rm Ag}(T) \times \left(1 - \frac{b}{t}\right)$$

and

$$\kappa_{\rm cal}^{(t)}(T) = \kappa_{\rm Ag}(T) \times \left(1 - \frac{a}{w}\right).$$

The similar fitting procedure was adopted for $\kappa(T)$ of the w- and t-samples, and then $a/w = 0.96$ and $b/t = 0.47$ were obtained independently. $(a/w) = 0.96$ multiplied by $(b/t) = 0.47$ equals to 0.45. The resultant value is consistent with the ab/wt value determined by the analysis for the l-sample, which supports the validity of our model. Consequently, we can conclude that the measured $\kappa(T)$ of the 'stacked' w- and t-samples correspond to those of the tape along w- and t- directions, because the thickness of the solder layer between the tapes is negligibly thin and the contact thermal resistance is ignored. The mechanism of the thermal transport for the w-direction almost the same as that for the l-direction. The value of $a/w = 0.96$ means that the applied heat flows through only about 4% of the total Ag region for the t-direction. The volume ratio of the edges of the tape to the whole tape, $V_{\rm edge}/V_{\rm tape}$, is roughly estimated to be 5% from Fig. 1. Therefore, $(a/w) = 0.96$ is a plausible value and we can conclude for the t-direction that the routes of the applied heat are both edges of the tape. We succeeded in explaining the anisotropic thermal conductivity of the Bi2223/Ag tape in the wide temperature range between 50 and 200 K by the simplified heat-flow model.

V. Conclusion

We have determined the temperature dependence of the thermal conductivity, $\kappa(T)$, of a silver sheathed Bi2223 (Bi2223/Ag) tape along three typical directions, the length, width and thickness. To estimate $\kappa(T)$ of the tape along the width and thickness directions, we prepared two stacked bundles consisting of several Bi2223/Ag tapes. $\kappa(T)$ of the tape along the length and width directions was 250 W $\rm m^{-1}$ $\rm K^{-1}$ at 77 K and coincided with each other. On the other hand, $\kappa(T)$ of the tape along the thickness direction was about one order of magnitude smaller than that of others, although the temperature dependence was almost similar. The measured $\kappa(T)$ of the samples can be regarded as the $\kappa(T)$ of the tape along the three directions. The measured $\kappa(T)$ was well reproduced by the calculated $\kappa(T)$ based on the equivalent heat current circuit. For three directions, the applied heat flows through the Ag sheath, the amount of which depends on the direction.

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