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Anisotropic thermal transport in double-pancake coil wound with DI-BSCCO® tape

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ABSTRACT

We have measured the temperature dependence of the thermal resistances $R_r(T)$ and $R_z(T)$ of the parallelepiped samples cut from a double-pancake coil along the radial (r) and the thickness (z) directions, respectively. The double-pancake coil was wound with DI-BSCCO® tape fabricated by Sumitomo Electric Industries, Ltd. DI-BSCCO is a $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+x}$ tape sheathed with silver. Both $R_r(T)$ and $R_z(T)$ increase monotonically with decreasing temperature. We analyze the thermal transport in the coil by use of the parallel and series heat current circuit of DI-BSCCO tapes and insulators.
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1. Introduction

DI-BSCCO® is a silver sheathed $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi2223) superconductive tape [1]. It has a high critical current density over 200 A at 77 K in the self-field [2] and a high mechanical strength [3] in comparison with other conventional Bi2223/Ag tapes. Because of the thermal stability in the superconducting apparatus, the thermal conductivity, $\kappa(T)$, is one of the most important physical properties [4]. It is well known that the absolute value and temperature dependence of κ for the Bi2223/Ag tapes strongly depend on the κ of the sheath material, the volume ratio of the sheath to the Bi2223 and fabrication processes [5]. We have measured $\kappa(T)$ for various types of DI-BSCCO [6]. $\kappa(T)$ of the stacked bundle, in which six DI-BSCCO tapes were soldered, was also measured [7]. Furthermore, $\kappa(T)$ of the sandwiched sample, in which the single DI-BSCCO tape was laminated from both sides by the thin alloy tapes (20–100 μm in thickness) was measured [8]. The obtained $\kappa(T)$ for the composite samples can be successfully described by the parallel circuit of the heat current using the $\kappa(T)$'s for the single DI-BSCCO tape, solder and alloy tape. A superconducting coil has a composite structure which consists of a superconducting tape and the insulators. In this paper, we investigate the anisotropic thermal transport along the radial and the thickness directions of the double-pancake coil wound with the DI-BSCCO tape using the thermal resistance measurement.

2. Experimental

Using the DI-BSCCO tape (type H) wrapt by an insulating Kapton tape, a double-pancake coil was prepared by a winding and react process and completed by epoxy impregnation. We measured the r- and z-samples cut from the coil along the radial and the thickness directions, as shown in the center of Fig. 1. The r-sample was cut from the upper pancake coil. The dimensions of the samples are shown in Table 1. The DI-BSCCO (type H) tape, which is a standard type, was fabricated by a powder in tube (PIT) method with the controlled overpressure (CT-OP) sintering technique [9].

Thermal resistance, $R(T)$, was measured by a steady-state heat flow method [10]. The experimental setup is schematically illustrated in Fig. 1. One end of the sample was adhered to the copper block using a silver paste (H20E). A small metal chip resistor (1 kΩ) which was used as a heater was adhered to the other end of the sample using GE7031 varnish. R is calculated by the relation:

$$R = \frac{\Delta T}{Q}, \tag{1}$$

where Q is the applied heat flow and ΔT the temperature difference between two chromel-constantan thermocouples (76 μm in diameter). ΔT was maintained to be approximately 1 K by controlling the heater power. The temperature of the sample stage was controlled using a Gifford–McMahon cycle helium refrigerator. To eliminate the radiation loss, R was measured below 250 K.

3. Results

Fig. 2a and b show the temperature dependence of the thermal resistance, $R(T)$, for the r- and z-samples, respectively. $R(T)$ for both samples increases monotonically with decreasing temperature. Inset of Fig. 2a shows the thermal conductivity, $\kappa(T)$, for the DI-BSCCO tape (type H) along the tape surface, $\kappa^{\parallel}{}_{SC}$ [6], the epoxy resin, κ_E [11], and the Kapton tape, κ_K [11], all of which are used in the analysis for the thermal transport in the next section.

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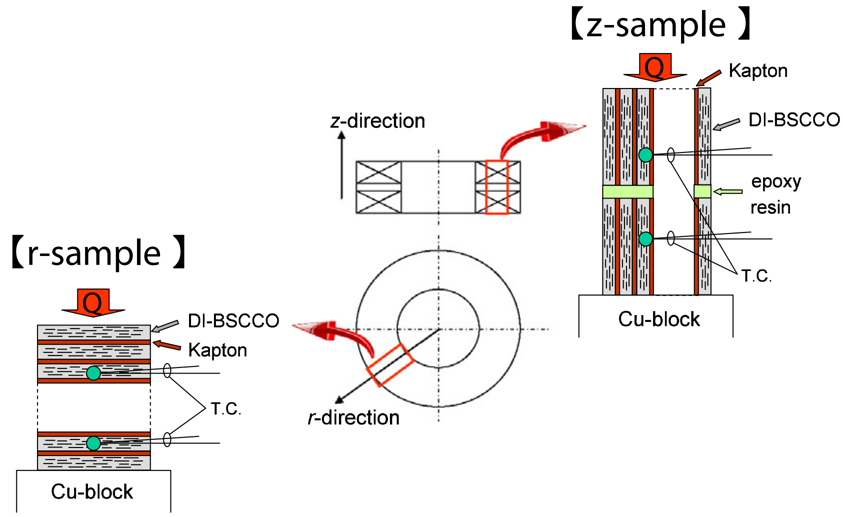

Fig. 1. (Center) Schematic view of the double-pancake coil. (Left and right) Experimental setup for the thermal conductivity measurement along the *r*- and *z*-direction.

Table 1
Dimensions of the samples.

	Length (mm)	Cross section (mm^2)
r-sample	15.1	16(= 4.0 × 4.0)
z-sample	9.1	16(= 4.0 × 4.0)

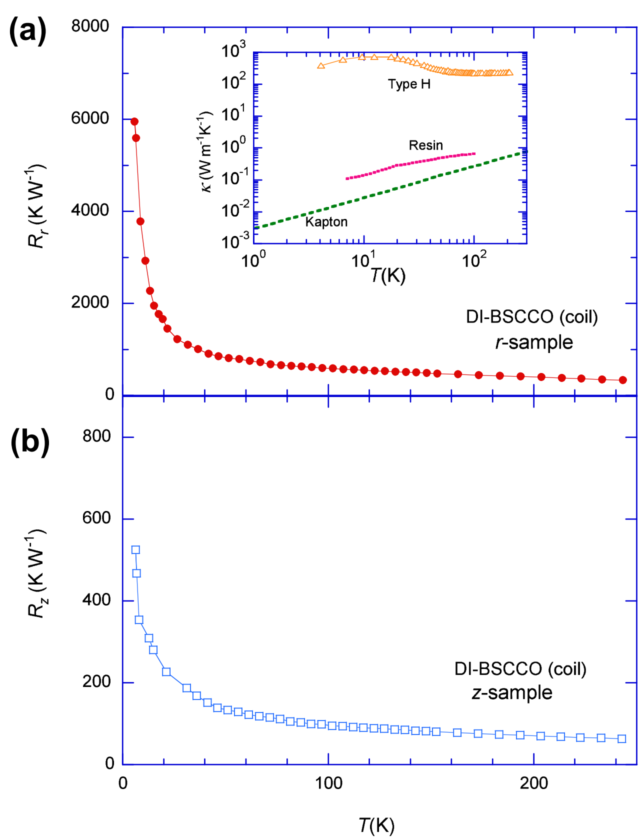

Fig. 2. Temperature dependence of the thermal resistance, $R(T)$, for (a) the *r*-sample and (b) *z*-sample. Inset of (a) shows the thermal conductivity, $\kappa(T)$, for the DI-BSCCO tape (type H) [6], the resin [11], and the Kapton tape [11].

4. Discussion

4.1. Analysis for thermal transport along the r-direction

As shown in the left of Fig. 3a, the DI-BSCCO tape and the Kapton sheets were stacked one after the other in the *r*-sample. For simplicity, all the pieces for DI-BSCCO tapes and Kapton sheets were virtually collected and stacked as shown in the middle of Fig. 3a. As a result, the equivalent heat current circuit can be represented in the right of Fig. 3a, where $R_{SC}^{\perp}$ is the thermal resistance of the DI-BSCCO tape perpendicular to the tape surface, i.e., along the *c*-axis of the Bi2223 filament and R_K is that of the Kapton sheet. Furthermore, R_{con} is the total thermal contact resistance at the interfaces between the DI-BSCCO tape and the Kapton sheet and between the Kapton sheets. The measured ΔT_r for the *r*-sample is given as:

$$\Delta T_r = \Delta T_{SC}^{\perp} + \Delta T_K + \Delta T_{con} = \left[R_{SC}^{\perp} + R_K + R_{con}\right] \times Q,$$

where $\Delta T_{SC}^{\perp}$, ΔT_K and ΔT_{con} are the temperature difference in the DI-BSCCO part, the Kapton part and the contact resistance part, respectively. At 77 K, the measured ΔT_r was 1.03 K and the applied heat flow Q was 0.0016 W. Using the reported value of $\kappa_K = 0.22\ W\,m^{-1}\,K^{-1}$ [11], $S_K = 16\ mm^2$ and $L_K = 1.33$ mm, $\Delta T_K(= R_K Q = [L_K/(\kappa_K \times S_K)]Q)$ was estimated to be 0.64 K, where S_K is the cross section and L_K the total thickness of the Kapton part, respectively. For the DI-BSCCO part in the *r*-sample, the applied heat current flows perpendicular to the tape surface.

Fig. 3b shows the photograph of the cross section of the DI-BSCCO tape. Black and white regions represent the Bi2223 filament and Ag region, respectively. Since the Bi2223 filaments separately distribute in the Ag region, the path of the heat current is quite complicated. To determine $R_{SC}^{\perp}$ analytically, we consider the simple parallel circuit as shown in Fig. 3c. Here, R_{Ag} and $R_{Bi2223}^{\parallel c}$ are the thermal resistance of Ag and the Bi2223 filament along the *c*-axis, respectively. $\kappa(T)$ of the Bi2223 single crystal along the *c*-axis has not been reported. Only the κ value for the Bi2223 polycrystal was reported to be about $3\ W\,m^{-1}\,K^{-1}$ at 77 K [10], which was two orders of magnitude smaller than that for Ag ($\sim$360 $W\,m^{-1}\,K^{-1}$ at 77 K) [12]. In this situation, the heat current flows through only the Ag parts [13], and the $\Delta T_{SC}^{\perp}(= R_{Ag}Q = [L_{Ag}/(\kappa_{Ag} \times S_{Ag})]Q)$ was estimated to be 0.002 K. $S_{Ag}(= 2.8 \times 4\ mm^2)$ is the effective cross section of the Ag part which is estimated using the volume ratio ($=1.8$) of Ag to the

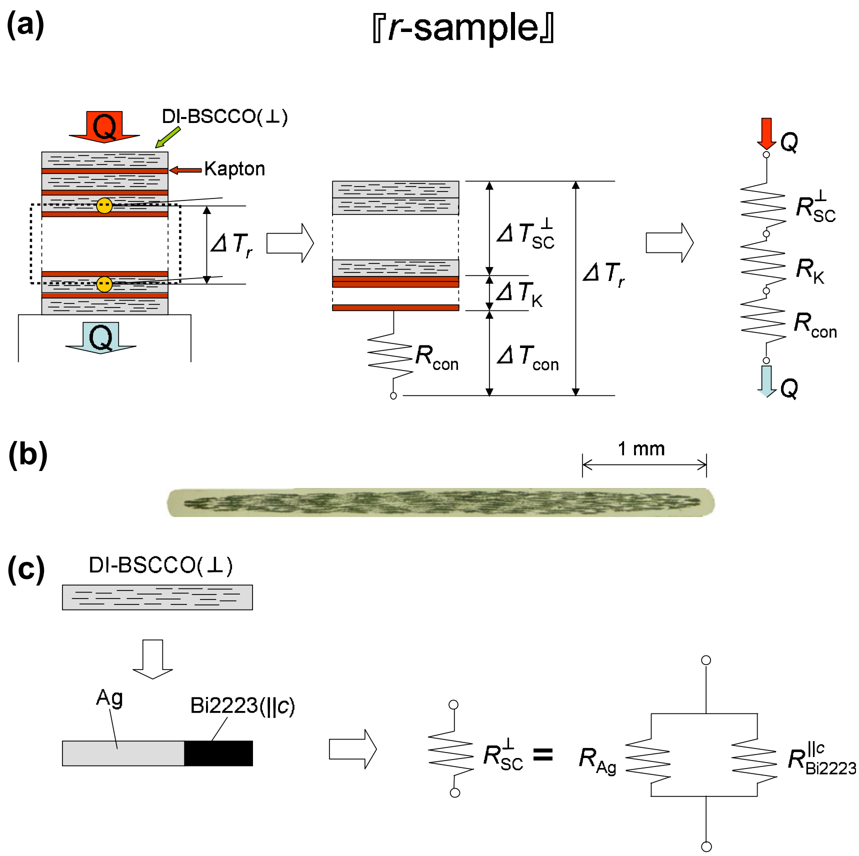

Fig. 3. (a) Equivalent heat current circuit for the *r*-sample. (b) Photograph of the cross section of DI-BSCCO tape. Black and white regions represent the Bi2223 filament and Ag region, respectively. (c) Equivalent heat current circuit perpendicular to the tape surface in the DI-BSCCO tape.

Bi2223 and L_{Ag}(= 4.4 mm) is the total thickness of the DI-BSCCO tape. The sum of ΔT_K and $\Delta T_{SC}^{\perp}$ ($\simeq$0.64 K) cannot reproduce the measured ΔT_r = 1.03 K, indicating that a large thermal contact resistance, R_{con}, exists and is estimated to be 260 K W^{-1} at the interfaces. R_{con} prevents greatly the flow of the heat current. It is noteworthy that the estimated R_{con} is not a universal value; R_{con} depends on the number and thickness of both DI-BSCCO tapes and Kapton sheets. We note that $R_{SC}^{\perp}$ obtained by the simple model mentioned above gives the lower limit. Since the thermal carriers are scattered at the surface of the Bi2223 filaments, $R^{\perp}_{SC}$ must be enhanced. To discuss more precisely the thermal transport along the *r*-direction, the thermal conductivity, $\kappa_{SC}^{\perp}$, perpendicular to the tape surface should be directly measured.

4.2. Analysis for thermal transport along the z-direction

As shown in the left of Fig. 4, two bundles, which consist of fourteen sheets of DI-BSCCO tapes and thirteen Kapton layers, are adhered by the epoxy resin in the *z*-sample. In each bundle, the applied heat current flows in parallel along the surface of the DI-BSCCO tape (i.e., the *ab*-plane of the Bi2223 filament) and the Kapton sheet. The equivalent heat current circuit in the *z*-sample

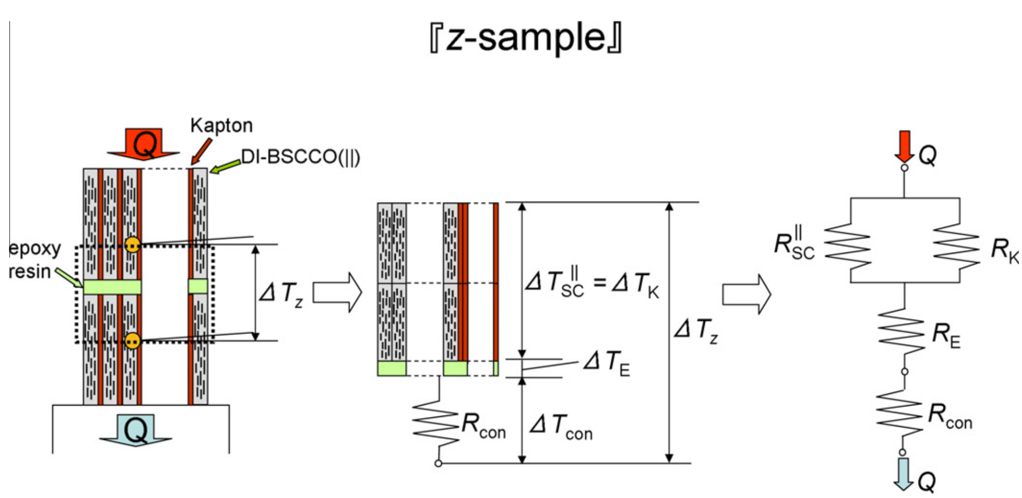

Fig. 4. Equivalent heat current circuit for the *z*-sample.

can be depicted in the right of Fig. 4, where $R^{\parallel}_{SC}$ and R_E are the thermal resistance for the DI-BSCCO tape along the tape surface and that for the epoxy resin, respectively. The measured ΔT_z for the z-sample is given as

$$\Delta T_z = \Delta T^{\parallel}_{SC} + \Delta T_E + \Delta T_{con} = \left[\left(\frac{1}{R^{\parallel}_{SC}} + \frac{1}{R_K}\right)^{-1} + R_E + R_{con}\right] \times Q$$
$$\simeq \left[R^{\parallel}_{SC} + R_E + R_{con}\right] \times Q,$$

where $\Delta T^{\parallel}_{SC}$ and ΔT_E are the temperature difference in the bundles and the epoxy resin, respectively. At 77 K, the measured ΔT_z was 1.05 K and the applied heater power Q was 0.0094 W. The reported κ_E is about 0.6 W m^{-1} K^{-1} at 77 K [11] and gives ΔT_E = 0.19 K using S_E = 16 mm^2 and L_E = 0.2 mm, where S_E and L_E are the cross section and the length of the epoxy resin part.

We can neglect the contribution of the Kapton layers to the heat transport because of $R_K \gg R^{\parallel}_{SC}$. Using κ = 230 W m^{-1} K^{-1} of the DI-BSCCO (type H) tape along the tape surface at 77 K [6], $S^{\parallel}_{SC}$ = 12 mm^2 and $L^{\parallel}_{SC}$ = 3.4 mm, the $\Delta T^{\parallel}_{SC}$ was estimated to be 0.16 K. $S^{\parallel}_{SC}$ is the cross section and $L^{\parallel}_{SC}$ is the total thickness of the DI-BSCCO tapes. The sum of the ΔT_E and $\Delta T^{\parallel}_{SC}$ is approximately 0.35 K. We cannot reproduce the measured ΔT_z = 1.05 K. These results indicate that ΔT_{con} is as large as 0.74 K and the large R_{con} of 79 K W^{-1} exists at the interface between the bundle and the epoxy resin and suppresses the heat transport in the z-sample. The R_{con} value in the z-sample changes depending on the length of the bundle $\left(L^{\parallel}_{SC}\right)$ and the thickness of the epoxy resin part (L_E).

A double-pancake coil might be cooled along the z-direction using the helium refrigerator. If a hot-spot creates in the upper pancake coil, the generated heat cannot be immediately exhausted to the cold stage because of the large R_{con} value, causing the temperature rise in the coil. Therefore, a cooling path for the upper coil should be considered.

5. Summary

We have measured the temperature dependence of the thermal resistance, $R(T)$, in the double-pancake coil wound with the DI-BSCCO tapes (type H) along the radial and the thickness directions using the parallelepiped samples cut from the coil. The thermal transport was analyzed using the equivalent heat current circuit and the thermal contact resistance, R_{con}, at the interface between the DI-BSCCO tape and the insulating separator was estimated. The R_{con} value affects strongly the thermal transport along both directions in the coil. Note that the obtained value of the thermal contact resistance is not a universal one, which depends on the condition of the interface between the materials. Using the results, the temperature rise in the coil can be estimated when a hot-spot creates. These analysis might play an important role in the design of the cooling system.

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