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Thermal conductivity of YBCO coated conductors fabricated by IBAD–PLD method

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Abstract
We have measured the temperature dependence of the thermal conductivity $\kappa(T)$ of YBCO coated conductor tapes with various thicknesses of stabilizing Ag layer and analyzed the measured $\kappa(T)$ using the equivalent heat current circuit. $\kappa(T)$ of the tape increased with increasing thickness of Ag layer. In the analysis, the dominant thermal carriers were found to be the electrons in the Ag layer in the entire temperature range. The thermal conductivity of the Ag layer, $\kappa_{\mathrm{Ag}}(T)$, was estimated to decrease with increasing thickness of Ag layer, which suggested that impurities and/or crystal defects were introduced during the long time deposition of Ag.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

It is well known that $YBa_2Cu_3O_{7-\delta}$ (YBCO) shows a high performance at 77 K under a magnetic field parallel to the c-axis, $B \parallel c$, in comparison with the Bi–Sr–Ca–Cu–O system. The decrease of the critical current density J_c of YBCO is not so large under the high magnetic field. The absolute value of J_c of the YBCO film has been improved by the introduction of various artificial vortex pinning centers (AVPCs) using nanotechnology [1]. Recently, AVPCs were also introduced to YBCO coated conductors (YCC) and $J_c(B \parallel c)$ at 77 K exceeded that of NbTi at 4.2 K [1]. A long superconducting wire with higher J_c is required for practical applications, and numerous studies have been developed by a number of researchers and companies [2]. Recently, YCC has just started to be used for prototype power electric applications such as power cables, motors, transformers, and fault current limiters [2].

The thermal conductivity $\kappa(T)$ of the tape is one of the essential physical properties in the design of superconducting equipment because it gives the heat flow Q_t through the tape [3] as follows,

$$Q_t = \frac{S}{L}\int_{T_1}^{T_2} \kappa(T)\,\mathrm{d}T.$$

In the equation, T_1 and T_2 are the temperatures of both terminals of the tape, S the cross section and L the length of the tape. YCC has a layered structure which consists of a metal substrate, buffer and cap layers, YBCO film, and a stabilizing Ag layer. The absolute value and temperature dependence of the thermal conductivity of the YCC tapes should depend on the species of each material, its purity and thickness. However, $\kappa(T)$ of YCC tapes has not been reported as far as we know. In this paper, we investigate the temperature dependence of the thermal conductivity $\kappa(T)$ of YCC tapes with various thicknesses of the stabilizing Ag layer. The measured $\kappa(T)$ was compared to the estimated one, which was calculated by the parallel heat flow model.

2. Experimental details

YCC was fabricated by an ion beam assisted deposition (IBAD) and a pulsed laser deposition (PLD) method.

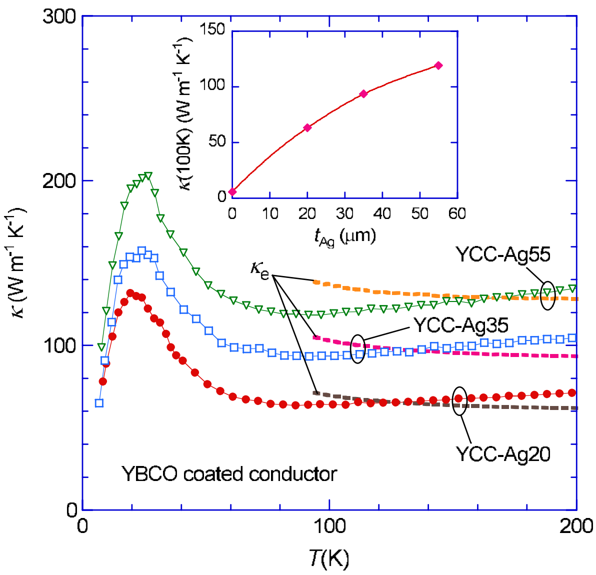

Figure 1. The temperature dependence of the thermal conductivity, $\kappa(T)$, for three YBCO coated conductors. The broken lines represent the electronic thermal conductivity, $\kappa_e(T)$, which is estimated from the electrical resistivity shown in figure 2. Inset shows the dependence on the thickness of the Ag layer of the κ value at 100 K, $\kappa(100\ \mathrm{K})$.

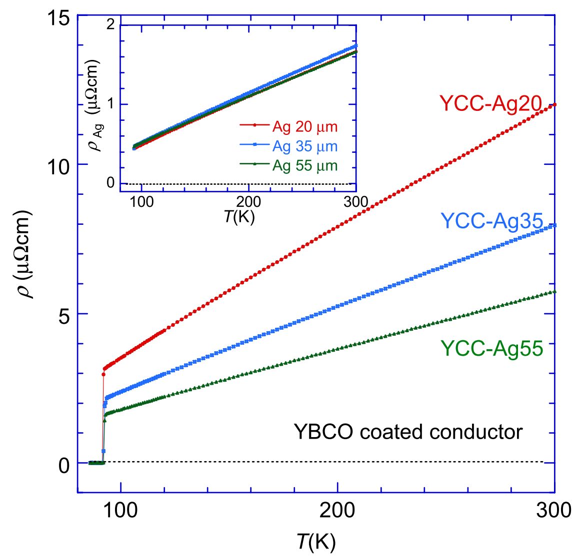

Figure 2. The temperature dependence of the electrical resistivity, $\rho(T)$, for three YBCO coated conductors (YCCs). Inset shows the estimated electrical resistivity of the Ag layer, $\rho_{Ag}(T)$, for three YCC tapes.

The details of sample preparation have been described elsewhere [4]. The substrate was Hastelloy C-276 (100 μm in thickness). $Gd_2Zr_2O_7$ (GZO) film (about 1 μm in thickness) was deposited on the Hastelloy as the buffer layer by the IBAD method. The cap layer of a CeO_2 film (0.7 μm in thickness) and YBCO film were prepared on the IBAD-GZO film by the PLD method. The thickness of the YBCO layer was approximately 1.5 μm. Finally, Ag was deposited on YBCO/CeO_2/GZO/Hastelloy as the thermal stabilizer. We prepared three YCC tapes with different Ag thickness t_{Ag}, 20, 35 and 55 μm. These were named YCC–Ag20, YCC–Ag35 and YCC–Ag55, respectively. To examine the contribution of the buffer and cap layers to the thermal transport, plain Hastelloy tape and CeO_2/GZO/Hastelloy tape were also prepared.

The thermal conductivity $\kappa(T)$ was measured by a steady-state heat flow method [5]. One end of the tape was soldered to the copper-block as a heat sink. A small metal chip resistor (1 kΩ) was adhered to the other end of the tape as a heater using GE7031 varnish. κ is given as $\kappa = (Q/\Delta T)\cdot(L/S)$, where Q is the applied heat flow, ΔT the temperature difference, L the distance between the two thermocouples, and S the cross section of the tape. ΔT was measured using two chromel–constantan thermocouples and maintained at about 1 K by controlling the electric current applied to the chip resistor. The electrical resistivity $\rho(T)$ was measured by a four-probe method with a typical current density of 5–7 A cm^{-2}. The temperature of the sample stage was controlled using a Gifford–McMahon cycle helium refrigerator and a 30 W heater. To eliminate the radiation loss, κ was measured below 200 K.

3. Results and discussion

Figure 1 shows the $\kappa(T)$ of three YCC tapes with various thicknesses of Ag layer t_{Ag}. For YCC–Ag20, $\kappa(T)$ decreases moderately with decreasing temperature from 200 K down to 85 K, begins to increase below 85 K, and reaches a maximum around 20 K. The absolute values of κ are 71 W m^{-1} K^{-1} at 200 K and 63 W m^{-1} K^{-1} at 77 K. The peak value of κ is approximately 130 W m^{-1} K^{-1}. The shape of $\kappa(T)$ for YCC–Ag35 and YCC–Ag55 is similar to that for YCC–Ag20. The absolute value of κ increases with increasing t_{Ag} because of the high thermal conductivity of the Ag layer, $\kappa_{Ag}(T)$. The inset of figure 1 shows the κ value at 100 K, $\kappa(100\ \mathrm{K})$, as a function of t_{Ag}, where the $\kappa(100\ \mathrm{K})$ value at $t_{Ag} = 0\ \mu$m is that of Hastelloy measured here. $\kappa(100\ \mathrm{K})$ is not proportional to t_{Ag}. YCC–Ag35 and YCC–Ag55 reach peaks of approximately 158 W m^{-1} K^{-1} near 24 K and approximately 203 W m^{-1} K^{-1} near 26 K, respectively. The observed peak is caused by the competition of the mean free path of the thermal carriers, l, and the specific heat, C, because of the relation, $\kappa = \frac{1}{3}Cvl$, where v is the mean velocity of the thermal carriers [6]. The shift of the peak temperature suggests a change in the purity of Ag layer, as observed in $\kappa(T)$ for various high-purity metals [7, 8].

Figure 2 shows the temperature dependence of the electrical resistivity $\rho(T)$ of three YCC tapes. The superconducting transition temperature T_c defined at the middle-point of the transition was approximately 92 K for all the tapes. All the $\rho(T)$ curves depend linearly on the temperature in the normal state. The absolute value of $\rho(T)$ decreases with increasing t_{Ag}. Assuming that the applied electric current flows through each conducting layer in parallel, we estimated the electrical resistivity of the Ag layer, ρ_{Ag}, above T_c by the reduced equation of the combined resistance, $\rho_{Ag} = \rho \times (t_{Ag}/t_{tape})$, where t_{tape} is the total thickness of the tape. As found in the inset of figure 2, all the $\rho_{Ag}(T)$ curves are scaled on the universal curve within the experimental error. Therefore, the applied electric current flows through the Ag layer in the normal state. The electronic thermal conductivity κ_e can be estimated roughly from $\rho(T)$ using the Wiedemann–Franz (WF) law, $\kappa_e = L_0 T/\rho$, where L_0 is the Lorenz number. The estimated κ_e's for three YCC tapes at 200–100 K are about 60–70 (YCC–Ag20), 90–105 (YCC–Ag35), and 130–140 W m^{-1} K^{-1} (YCC–Ag55), respectively. The estimated $\kappa_e(T)$ curves are shown in figure 1 and are roughly comparable to the measured $\kappa(T)$, suggesting that the dominant thermal carriers in the normal state are the electrons in the Ag layer for all the YCC tapes.

We attempt to estimate $\kappa(T)$ of the YCC tapes approxiamately using $\kappa(T)$ of each elemental material such as CeO_2/GZO/Hastelloy, YBCO, and Ag. The schematic image of the heat flow through a layered sample which consists of n kinds of materials is shown in figure 3(a). We assume that the heat flows through each layer in parallel. The total applied heat Q_{tot} is written as

$$Q_{tot} = \sum_{i=1}^{n} Q_i.$$

Q_i is the heat flow through the ith layer, which depends on the thermal conductance of each layer κ_i^{-1}. Since ΔT and L are the same for all the layers, the total thermal conductivity, κ_{tot}, can be estimated by

$$\kappa_{tot} = \left(\sum_{i=1}^{n} (\kappa_i \times S_i) \right) \Big/ S_{tot}.$$

S_i and S_{tot} are the cross section for the ith layer and the tape, respectively. Figures 3(b) and (c) show the temperature dependence of the measured and calculated thermal conductivity, $\kappa(T)$ and $\kappa_{cal}(T)$, of YCC–Ag20 and YCC–Ag55. The reported $\kappa(T)$ of Ag–Au alloy [7, 9] and that in the ab-plane of YBCO superconducting bulk [5] are also plotted. The measured $\kappa(T)$ curves of Hastelloy and CeO_2/GZO/Hastelloy tapes almost coincide with each other, meaning that the contribution of both buffer and cap layers to the thermal transport is negligibly small. The absolute value of $\kappa(T)$ for Hastelloy is about one tenth of that for YCC–Ag20 at 100 K. As seen in figure 3(b), $\kappa(T)$ of YCC–Ag20 is reproduced well by $\kappa_{cal}(T)$, when $\kappa_{Ag}(T)$ of Ag–0.09 at.%Au alloy was used. On the other hand, the measured $\kappa(T)$ of YCC–Ag55 was between $\kappa_{cal}(T)$ using $\kappa_{Ag}(T)$ of Ag–0.09 at.%Au alloy and that using $\kappa_{Ag}(T)$ of Ag–0.22 at.%Au alloy. These results suggest that the absolute value of $\kappa_{Ag}(T)$ of the Ag layer in YCC–Ag55 is lower than that in YCC–Ag20. The impurity content in the Ag layer increased for the YCC–Ag55 sample and/or crystal defects corresponding to the amount of impurity were introduced during the deposition of the Ag layer. Other residual substances in the chamber are possible impurities, which will be examined using an electron probe micro analyzer (EPMA) and inductively coupled plasma (ICP) spectroscopy. We plan to evaluate the crystal defects using a scanning electron microscope (SEM). Consequently, the dominant thermal carriers are the electrons in the Ag layer above and below T_c for the YCC tapes.

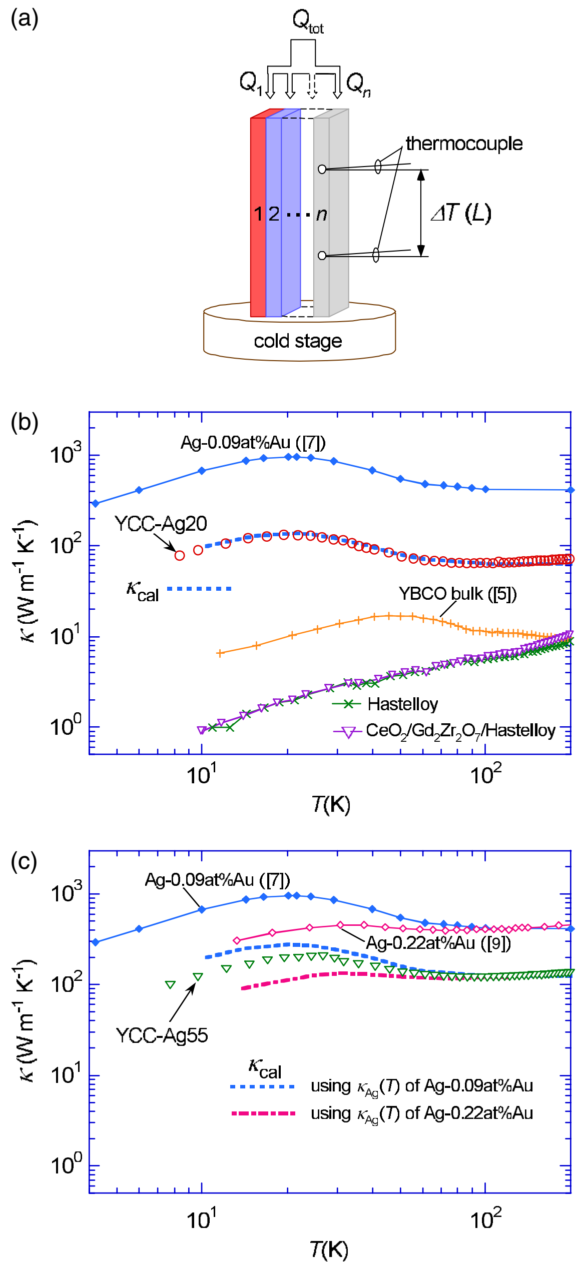

Figure 3. (a) A schematic image of the heat flow through a layered sample consisting of the n-kinds of layers. (b) and (c) show the measured and calculated thermal conductivity, $\kappa(T)$ and $\kappa_{cal}(T)$, for YCC–Ag20 and YCC–Ag55, respectively. $\kappa(T)$ for the Ag–0.09 at.%Au [7], Ag–0.22 at.%Au [9] and YBCO bulk [5] are reported values. The measured $\kappa(T)$ of Hastelloy and CeO_2/GZO/Hastelloy tapes is also shown.

4. Summary

We have measured the temperature dependence of the thermal conductivity $\kappa(T)$ of three YBCO coated conductors (YCCs) with different thicknesses of the Ag layer. $\kappa(T)$ showed a peak around 20 K because of the $\kappa_{Ag}(T)$ of the stabilizing Ag layer. The absolute value of $\kappa(T)$ increased with increasing thickness of the Ag layer. The thermal conductivity $\kappa(T)$ was compared to the calculated thermal conductivity $\kappa_{cal}(T)$ using the equivalent heat current circuit. As a result, the dominant thermal carriers were the electrons in the Ag layer. The magnitude of $\kappa_{Ag}(T)$ of the Ag layer was suppressed in thicker Ag layers. A possible reason is that the purity of the Ag layer decreased with increasing thickness or that crystal defects were introduced during long time deposition. $\kappa(T)$ of Hastelloy and buffer and cap layers deposited on the Hastelloy are less than one tenth of $\kappa(T)$ of YCC tapes stabilized with Ag layers.

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