Thermal Conductivity of YBCO Coated Conductors Reinforced by Metal Tape

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***Abstract*—We have measured the thermal conductivity, $\kappa(T)$, of YBCO coated conductors (YCCs) reinforced by Cu or CuNi tape. $\kappa(T)$ of YCC reinforced by Cu tape with 100–300 $\mu\mathrm{m}$ in thickness, YCC-Cu, was 250–400 W $\mathrm{m}^{-1}\mathrm{K}^{-1}$ at 77 K, which depended on the thickness of Cu tape and was roughly one order of magnitude larger than that of the bare YCC. On the other hand, $\kappa(T)$ of YCC reinforced by CuNi tape of 300 $\mu\mathrm{m}$ thickness, YCC-CuNi, was comparable to that of the bare YCC except for the low temperatures. The contribution of each reinforcing material to the thermal transport was estimated by analyzing the measured $\kappa(T)$ using an equivalent heat current circuit. The applied heat flows mainly through the Cu tape for the YCC-Cu tapes and through both CuNi tape and stabilizing Ag layer for the YCC-CuNi tapes, respectively. Phonons cannot be ignored as thermal carriers in YCC-CuNi tapes.**

***Index Terms*—Specific heat, thermal conductivity, YBCO coated conductor.**

I. INTRODUCTION

A Bi2223 superconducting tape sheathed with silver, Bi2223/Ag, has already been commercially provided by several companies. Recently, a high critical current over 200 A at 77 K under the self-field was achieved [1], [2], which has a high potential for the practical applications. However, the operating temperature of the Bi2223/Ag tapes is limited to temperatures lower than 20 K, because their critical current density, J_{c}, decreases rapidly with increasing magnetic field at temperatures as high as 77 K [3]. On the other hand, the degradation of J_{c} of $\mathrm{YBa_2Cu_3O_{7-\delta}}$ (YBCO) is not as large even at 77 K under a high magnetic field as that of Bi2223/Ag tapes [4]. The J_{c} value of YBCO film has been recently enhanced by introduction of artificial vortex pinning centers (AVPCs) employing nanotechnology [5]. The AVPC-introduced YBCO film showed a high J_{c} value of over 0.1 $\mathrm{MA/cm^2}$ at 77 K in magnetic fields parallel to the c-axis up to about 8 T. This J_{c} exceeds that of NbTi and $\mathrm{Nb_3Sn}$ at 4.2 K [5]. Therefore, YBCO film is one of the most promising materials that can be used practically in power applications operated at 77 K. YBCO coated conductor (YCC) tape, which consists of metal substrate, buffer and cap layers, YBCO film, and stabilizing Ag layer, has been developed. Recently, the YCC tapes have just started to be used for prototype of power electric applications such as power cables, motors, transformers, and fault current limiters [6].

Thermal conductivity, $\kappa(T)$, of the tape is one of the important physical properties in the design of a superconducting equipment, because we can estimate the amount of the heat flow, Q_{t}, through the tape as follows:

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

In the equation, T_1 and T_2 are the temperatures of the terminals of the tape; S the cross section; and L the length of the tape. Quite recently, we measured the temperature dependence of the thermal conductivity, $\kappa(T)$, of YCC tapes and the dominant thermal carriers were found to be the electrons in the stabilizing Ag layer [7]. The volume fraction of the Ag layer to the whole tape, f_{Ag}, is roughly estimated to be 10–30% for YCC, where the thickness of the Ag layer is 10–30 $\mu\mathrm{m}$ and that of Hastelloy substrate is 100 $\mu\mathrm{m}$. On the other hand, f_{Ag} of a conventional Bi2223/Ag tape is approximately 60% [8], [9]. The small f_{Ag} value of YCC is preferable because of the cost reduction; however it might cause poor thermal stability. To improve the thermal stability and mechanical strength simultaneously, the YCC tape is usually reinforced by a metal tape. In this paper, we measured the temperature dependence of $\kappa(T)$ of the YCC tapes reinforced by Cu or CuNi tape along the length direction, and discuss the effect of the reinforcing metal on thermal transport by comparing the measured $\kappa(T)$ with that estimated from a parallel heat flow model. The temperature dependence of the specific heat, $C(T)$, of the bare YCC tape was also measured. This is an important parameter in view of the estimation of the thermal stability.

II. EXPERIMENTAL

A. Sample

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

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TABLE I
SPECIFICATIONS OF THE YCC TAPES

Sample name	thickness of Ag layer (μm)	reinforcing metal
YCC-Ag10Cu100	10	Cu (100 μm)
YCC-Ag10Cu300	10	Cu (300 μm)
YCC-Ag20CN300	20	CuNi (300 μm)
YCC-Ag30CN300	30	CuNi (300 μm)
YCC-Ag20	20	–

The details of sample preparation have been described elsewhere [10]. The substrate material was Hastelloy C-276 (5 mm wide and 100 $\mu\mathrm{m}$ thick). $\mathrm{Gd_2Zr_2O_7}$ (GZO) film (about $1\mu\mathrm{m}$ thick) was deposited on the Hastelloy as a buffer layer by the IBAD method. The cap layer of $\mathrm{CeO_2}$ film (0.7 μm thick) and the YBCO film (about 1.5 $\mu\mathrm{m}$ thick) were prepared on the IBAD-GZO film by the PLD method. Finally, Ag was deposited on YBCO/$\mathrm{CeO_2}$/GZO/Hastelloy as the thermal stabilizer. We prepared YCC tapes reinforced by Cu or CuNi tape, which were named YCC-Cu or YCC-CN. In YCC-Cu tapes, the thickness of Ag layer was fixed at 10 $\mu\mathrm{m}$ and that of Cu tape at 100 or 300 $\mu\mathrm{m}$. In YCC-CN tapes, the thickness of Ag layer was 20 or 30 $\mu\mathrm{m}$ and that of CuNi tape was fixed at 300 $\mu\mathrm{m}$. The measured sample names and the thicknesses of Ag and of the reinforcing metal are described in Table I.

B. Measurements

Thermal conductivity, $\kappa(T)$, was measured by a steady-state heat flow method. One end of the tape was attached to a copper-block as a heat sink using In solder. 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 $\kappa=(Q_\mathrm{a}/\Delta T)\cdot(L/S)$, where Q_a is the applied heat flow, ΔT the temperature difference; L(typically 10 mm) the distance between the two thermocouples; and S the cross section of the tape. ΔT was measured using two chromel-constantan thermocouples and was maintained at about 0.5–0.7 K by automatically controlling the heater power. Electrical resistivity, $\rho(T)$, was measured by a four-probe method. 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. Specific heat, $C(T)$, was measured by a relaxation technique using the Physical Properties Measurement System (PPMS, Quantum Design Inc.).

III. RESULTS AND DISCUSSION

A. Thermal Conductivity

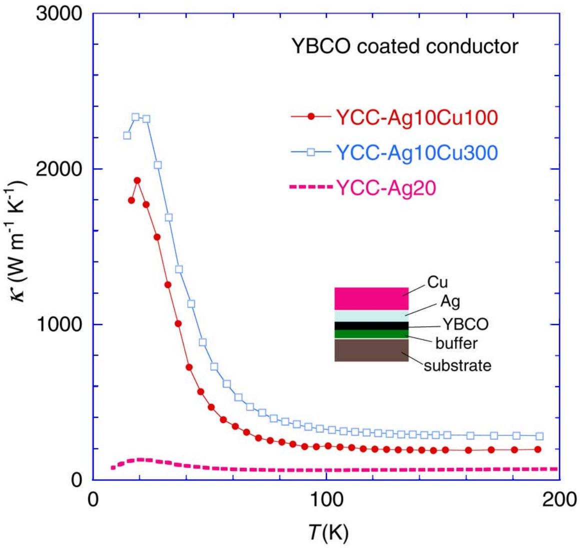

Fig. 1. Temperature dependence of the thermal conductivity $\kappa(T)$ of YCC and YCC-Cu tapes.

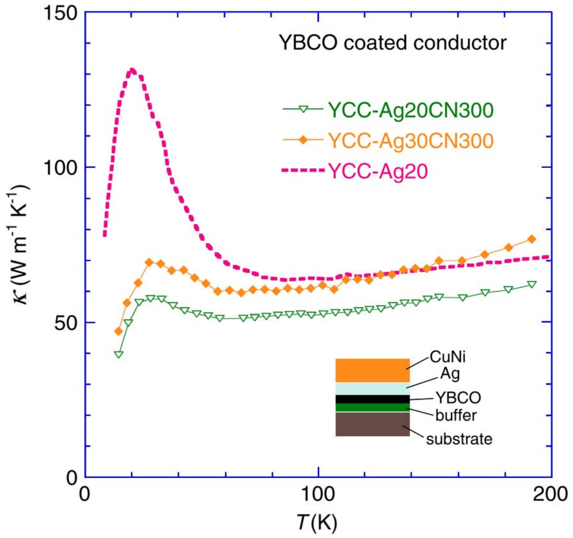

Fig. 2. Temperature dependence of the thermal conductivity $\kappa(T)$ of YCC and YCC-CuNi tapes.

Fig. 1 shows $\kappa(T)$ of the YCC-Cu tapes. The reported $\kappa(T)$ of bare YCC tape with a 20 μm thick Ag layer [7], denoted by YCC-Ag20, is also plotted. $\kappa(T)$ of YCC-Cu tapes increases slightly with decreasing temperature, begins to increase rapidly below 90 K, and takes a maximum of approximately 2000–2400 $\mathrm{W\ m^{-1}K^{-1}}$ around 20 K. The absolute value of $\kappa(T)$ at 77 K is about 250 $\mathrm{W\ m^{-1}K^{-1}}$ for YCC-Ag10Cu100 and about $400\mathrm{m^{-1}K^{-1}}$ for YCC-Ag10Cu300. The absolute value of $\kappa(T)$ of YCC-Cu tapes increases with increasing thickness of Cu tape. $\kappa(T)$ value of YCC-Ag20 at 77 K is about one order of magnitude smaller than that of YCC-Cu tapes.

Fig. 2 presents $\kappa(T)$ of two YCC-CN and YCC-Ag20 tapes. $\kappa(T)$ of the YCC-CN tapes monotonically decreases with decreasing temperature and shows a bump structure around 30 K. The absolute value of $\kappa(T)$ of the YCC-CN tapes at $T>60$ K is comparable to that of the YCC-Ag20 tape and increases with increasing thickness of the Ag layer.

Fig. 3 shows $\rho(T)$ of all the YCC-Cu and YCC-CuNi tapes. $\rho(T)$ of the YCC-Ag20 is also presented. The superconducting transition occurs at around 90 K for all the tapes. The temperature dependence of $\rho(T)$ is almost linear for the YCC-Cu tapes and its magnitude of $\rho(T)$ decreases with increasing thickness of Cu tape. On the other hand, $\rho(T)$ for YCC-CN tapes shows a positive curvature, $d^2\rho/dT^2>0$, and the magnitude of $\rho(T)$ decreases with increasing thickness of Ag layer. We

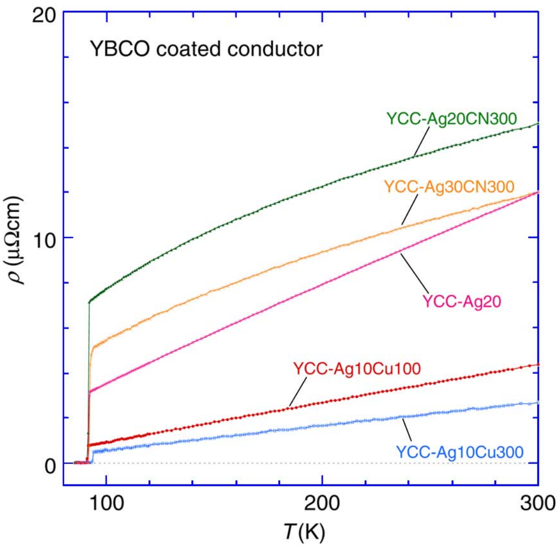

Fig. 3. Temperature dependence of the electrical resistivity $\rho(T)$ of YCC, YCC-Cu, and YCC-CuNi tapes.

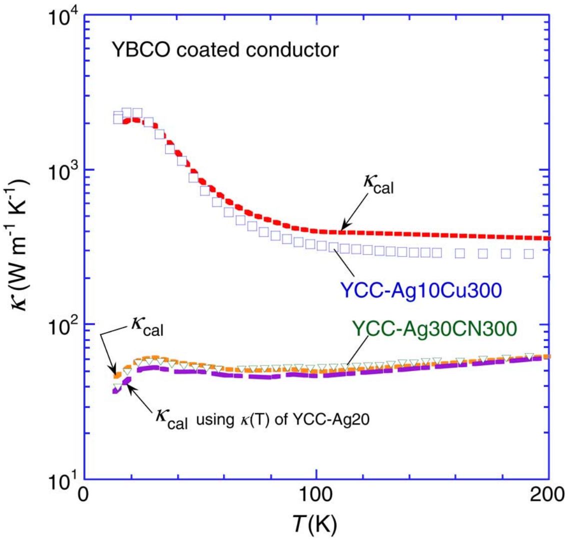

Fig. 4. Temperature dependence of the measured and calculated thermal conductivity $\kappa(T)$ of the YCC-Ag10Cu300 and YCC-Ag20CN300 tapes.

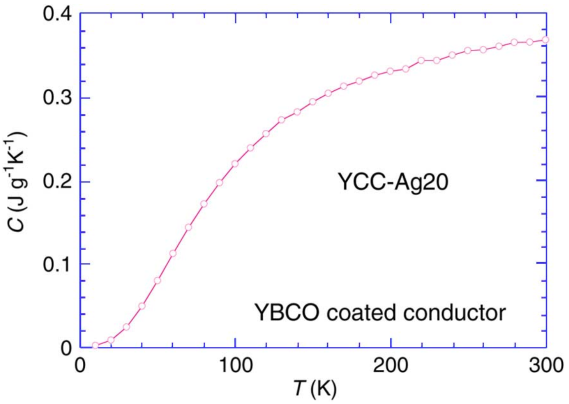

Fig. 5. Temperature dependence of the specific heat $C(T)$ of the YBCO coated conductor tape.

can estimate the electronic thermal conductivity, $\kappa_{\mathrm{e}}(T)$, from $\rho(T)$ using the Wiedemann-Franz law, $\kappa_{\mathrm{e}} = L_0 T/\rho$, where L_0 is the Lorenz number. The κ_{e} values at 200 K, $\kappa_{\mathrm{e}}(200\ \mathrm{K})$'s, for YCC-Ag10Cu100 and YCC-Ag10Cu300 are estimated to be 180 and 300 $\mathrm{W\ m^{-1}K^{-1}}$, respectively, which are roughly comparable to the measured $\kappa(200\ \mathrm{K})$ value. The $\kappa_{\mathrm{e}}(200\ \mathrm{K})$ values are about 40 and 52 $\mathrm{W\ m^{-1}K^{-1}}$ for YCC-Ag20CN300 and YCC-Ag30CN300 tapes, respectively, which are about 70% of the measured $\kappa(200\ \mathrm{K})$ value. These results suggest that the applied heat is transported dominantly by electrons in both the Ag layer and the reinforcing metal tape and that the contribution of phonons to thermal transport cannot be ignored for the YCC-CN tapes.

The amount of the contribution of each layer to thermal transport can be estimated by an equivalent heat current circuit as follows. In a multi-layered sample consisting of n layers, the total applied heat, Q_{tot}, is assumed to flow through each layer in parallel. If heat flow through the jth layer is written as Q_j, Q_{tot} is given by:

$$Q_{\mathrm{tot}} = \sum_{j=1}^{n} Q_j.$$

Since ΔT and L are the same for all layers, the total thermal conductivity, κ_{tot}, can be estimated from:

$$\kappa_{\mathrm{tot}} = \frac{\sum_{j=1}^{n}(\kappa_j \times S_j)}{S_{\mathrm{tot}}},$$

where κ_j is the thermal conductivity of the j-th layer and S_j and S_{tot} are the cross section of the j-th layer and of the sample, respectively. Fig. 4 shows the temperature dependence of the measured and calculated thermal conductivities, $\kappa(T)$ and $\kappa_{\mathrm{cal}}(T)$, for YCC-Ag10Cu300 and YCC-Ag20CN300. $\kappa_{\mathrm{cal}}(T)$ was calculated using $\kappa(T)$ of Hastelloy, Cu and Ag, because the contributions of the buffer and YBCO layers can be ignored due to their small $\kappa(T)$ [7] and a slight thicknesses. In the calculation, we used the measured $\kappa(T)$ of the Cu tape. Since the purity of the stabilizing Ag layer in the present YCC was estimated to be about 99.9% from the $\kappa(T)$ measurement [7], the reported $\kappa(T)$ of Ag-0.09at%Au alloy [11] was used in this calculation. $\kappa_{\mathrm{cal}}(T)$ for YCC-Ag20CN300 was also estimated using $\kappa(T)$ of YCC-Ag20 and CuNi tapes. The measured $\kappa(T)$ for both tapes is roughly reproduced by the calculated $\kappa_{\mathrm{cal}}(T)$. Although differences were observed above 80 K, the reinforcing Cu tape dominates thermal transport for the YCC-Cu tapes. On the other hand, the applied heat flows through both the CuNi tape and the Ag layer for YCC-CN tapes. Hastelloy tape can be ignored as the heat current path in each tape.

B. Specific Heat

Fig. 5 shows the temperature dependence of the specific heat, $C(T)$, of the YCC-Ag20 tape. $C(T)$ of YCC-Ag20 decreases monotonically with decreasing temperature. The temperature dependence and absolute value of $C(T)$ roughly correspond to those of Hastelloy [12]. Using the reported $C(T)$ value for Cu and CuNi, we can estimate the $C(T)$ value of the YCC reinforced by the metal tape using the $C(T)$ values of the YCC and the reinforcing metal tape.

IV. SUMMARY

We have measured the temperature dependence of the thermal conductivity, $\kappa(T)$, of various YBCO coated conductor (YCC) tapes with 10–30 $\mu\mathrm{m}$ Ag layer reinforced by Cu (100 or 300 $\mu\mathrm{m}$ thick) or CuNi (300 $\mu\mathrm{m}$ thick) tape. $\kappa(T)$ of YCC-Cu tape increased slightly with decreasing temperature, started to increase rapidly below 90 K, and took a maximum around 20 K. The absolute value of $\kappa(T)$ at 77 K was 250–400 W $\mathrm{m}^{-1}\mathrm{K}^{-1}$, depending on the thickness of Cu tape and was about 5–8 times larger than that of the bare YCC tape. On the other hand, $\kappa(T)$ of YCC-CuNi tapes decreased monotonically with decreasing temperature and showed a bump structure around 30 K. Their $\kappa(T)$ values were about 50–60 W $\mathrm{m}^{-1}\mathrm{K}^{-1}$ at 77 K, which is comparable to that of bare YCC tape. By assuming that the applied heat flowed through each layer of the tape in parallel, we analysed the measured $\kappa(T)$ using the calculated $\kappa(T)$. The dominant thermal carriers were the electrons in the reinforcing Cu region for the YCC-Cu tapes, which originated from the high thermal conductivity of Cu. For the YCC-CuNi tapes, although the applied heat mainly flows through both Ag layer and CuNi layer in parallel, the contribution of phonons to the thermal transport cannot be ignored. We also measured the temperature dependence of the specific heat, $C(T)$, of the bare YCC tape with 20 $\mu\mathrm{m}$ Ag layer, which was roughly comparable to that of Hastelloy. Using the $C(T)$ values reported for the metals, $C(T)$ of the YCC tape reinforced by various kinds of metal tape can be estimated by summing both $C(T)$ values of YCC and reinforcing metal tapes.

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