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Thermal conductivity of REBCO tapes with different stabilizers at 4.2 – 200 K

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Abstract. In REBCO current leads, it is important to minimize the thermal conduction while maintain stable electrical conduction. Therefore, thermal transport property of REBCO tapes need to be characterized. We measured thermal conductivity of REBCO tapes in the longitudinal direction at 4.2 - 200 K. Samples with Ag, Ag-3at%Au and Cu stabilizers of various thicknesses were measured. The residual-resistance-ratio (RRR) of these stabilizers were also measured and correlated with thermal conductivity. For samples with 10 μm or thicker Cu stabilizer (50 μm substrate), thermal conductivity is dominated by the Cu contribution. The sample with Ag-3at%Au stabilizer has significantly lower thermal conductivity than that with Ag stabilizer. It is concluded that REBCO with Ag-3at%Au stabilizer is promising for current lead applications.

1. Introduction

REBCO coated conductor is a high temperature superconductor that has wide range of applications in nuclear fusion, high energy physics and high-field research magnets. One of the applications is the current leads which allows current injection from the power supply to superconducting magnets that are at cryogenic temperatures. In the design of current leads, it is desirable to minimize the thermal conduction via REBCO coated conductor. To reduce the thermal conduction of the current leads, the fraction of the stabilizer, typically Cu, should be reduced. Further reduction of thermal conduction requires a stabilizer material with lower thermal conductivity. The longitudinal thermal conductivity of REBCO tapes with Cu stabilizers have been studied previously [1] - [6]. This paper focuses on the effect of different stabilizer materials. Thermal conductivity of REBCO tapes stabilized by Cu, Ag and Ag-Au alloy was measured and compared with simulations. Small discrepancies between the measured data and the simulations are discussed.

2. Experimental

The samples measured in this work are 4 mm wide REBCO tapes grown on 50 μm Hastelloy substrate by SuperPower Inc. Five samples with different stabilizers were prepared for thermal conductivity measurements. The total thickness of the samples was measured by using a digital micrometer. The details of the samples are tabulated in Table I.

Thermal conductivity was measured from 4.2 - 200 K by the thermal transport option of a physical property measurement system made by Quantum Design Inc. [7]. Four thermal leads were attached to the sample by a Ag-filled epoxy (Epoxy Technology H20E) cured at 120 C for 15

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minutes as depicted in Figure 1. The measurement was taken while the system temperature was slowly ramping up from 3 K (the continuous mode). The ramp rate was 0.2 K/min from 3 – 20 K, and 0.5 K/min from 20 – 200 K. The measurement error of thermal conductivity was estimated to be less than 10%.

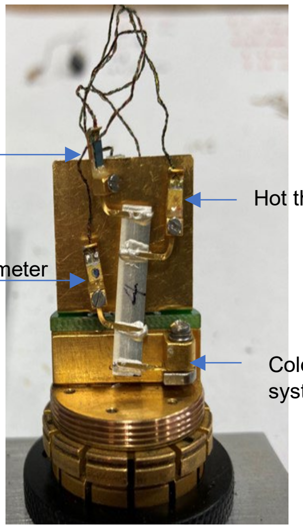

Figure 1. A REBCO sample mounted on the PPMS-TTO puck.

Table I Details of REBCO samples with different stabilizers and 50 μm substrate

No.	Stabilizer material	Stabilizer thickness (μm)	Measured total thickness (μm)	Measured stabilizer RRR	Simulated stabilizer RRR
1	Plated Cu	100*	145.8	133	108
2	Plated Cu	40*	92.8	58	63
3	Plated Cu	10*	61.2	31	25
4	Sputtered Ag	3	53	12.8	8 (Cu)
5	Sputtered Ag-3at%Au	3	53.2	2.3	-

* The thickness includes 1.5 μm Ag on each side of the tape.

The residual resistance ratio (RRR) of the stabilizers defined as the ratio of resistance at 295 K and that at 4.2 K was also measured. For Cu stabilized samples, the Cu layers were peeled from the substrate, and etched by HNO_3: H_2O = 3 : 500 to remove the residual superconductor. The thin Ag layer remained with Cu for RRR measurements. The stabilizers of sample 4 and 5 were too thin to peel. In those cases, the stabilizer on the REBCO side and the REBCO layer were removed by chemical etching with HNO_3: H_2O = 1 : 1, while the stabilizer on the substrate side was protected by a Kapton tape. Resistance of stabilizer/substrate composite was measured, from which the stabilizer's RRR was calculated.

a Thermal Scientific Helios G4 UC dual-beam field-emission SEM was used for cross-sectional microanalysis which including cross-section cutting by the focused-ion-beam and chemical analysis by energy dispersive spectroscopy (EDS).

3. Results and discussions

3.1 The Ag and Ag-Au stabilizer characterization

SEM was used to characterize Ag and Ag-Au stabilizers. A typical image is shown in Figure 2. The total thickness Ag and Ag-Au stabilizers were about 3 μm (1.5 μm per side). The composition of Ag-Au stabilizer was characterized by EDS to be Ag-3at%Au.

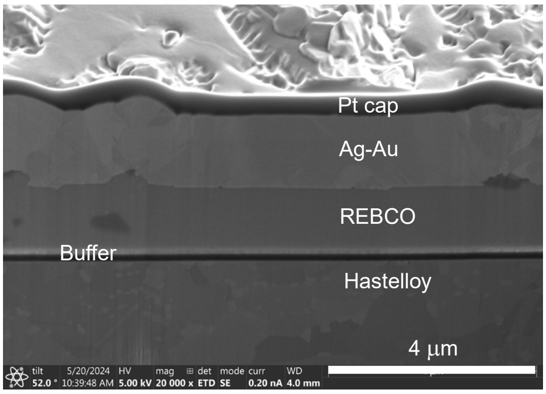

Figure 2. SEM examination of sample 5 which was stabilized by sputtered Ag-3at%Au.

3.2 RRR of stabilizer

The measured RRR of the stabilizers of each sample are listed in Table 1. For Cu stabilizers, RRR increases with its thickness. This is consistent with Ref. [8] where RRR increases with Cu grain size which increases with thickness of electroplated Cu film. The RRR of the thin Ag and Ag-3at%Au is comparable with values reported in [8] and [10] respectively.

3.3 Thermal conductivity

The measured thermal conductivity is shown in Figure 3. For samples with 100, 40, and 10 μm Cu stabilizers, thermal conductivity increases with Cu stabilizer thickness. This agrees with intuition. Since Cu is a much better thermal conductor than the substrate, higher fraction of the Cu leads to higher total thermal conductivity. Between the two samples with 3 μm stabilizers, Ag-3at%Au stabilized REBCO has significantly lower thermal conductivity than the Ag stabilized one.

To better understand our results, we calculate the thermal conductivity of multilayered REBCO tapes by considering the contribution from each layer. In a layered structure, the in-plane heat conduction of the layers is in parallel. Therefore, the total thermal conductivity follows the rule of mixture,

$$\kappa = \Sigma \kappa_i (t_i/t) \quad (1)$$

where κ and κ_i are the total thermal conductivity and that of the i^{th} layer respectively, t and t_i as the total thickness and that of the i^{th} layer respectively.

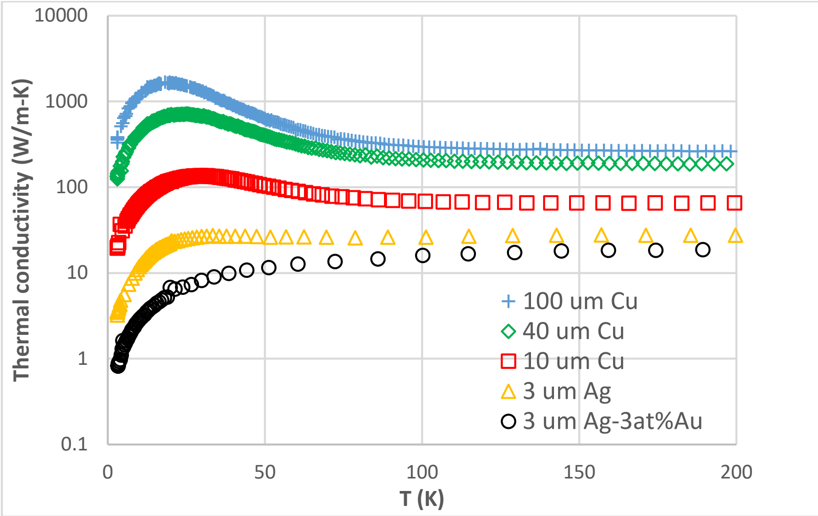

Figure 3. Measured thermal conductivity of 5 samples with different stabilizers.

According to equation (1) for layer *i* with low thermal conductivity and small thickness, $k_i t_i$ is small. Evidently its contribution to the total thermal conductivity is negligibly small. For this reason, in the following discussions we will ignore the contribution by the buffer layer of about 0.3 μm (as shown in Figure 2), which is less than 0.6% of the total thickness even for the samples of small total thickness (sample 4 and 5).

We calculated the thermal conductivity of each sample using equation (1). For these calculations, material thermal conductivities of each layer were obtained from the literature and reproduced as shown in Figure 4. Thermal conductivity of Cu strongly depends on its RRR and can be calculated using an empirical formula given by Ref. [9]. RRR value of Cu was used as a free parameter to simulate the measured thermal conductivity vs. *T* curve. The RRR values obtained by simulating thermal conductivity curves are listed together with electrically measured ones in Table I.

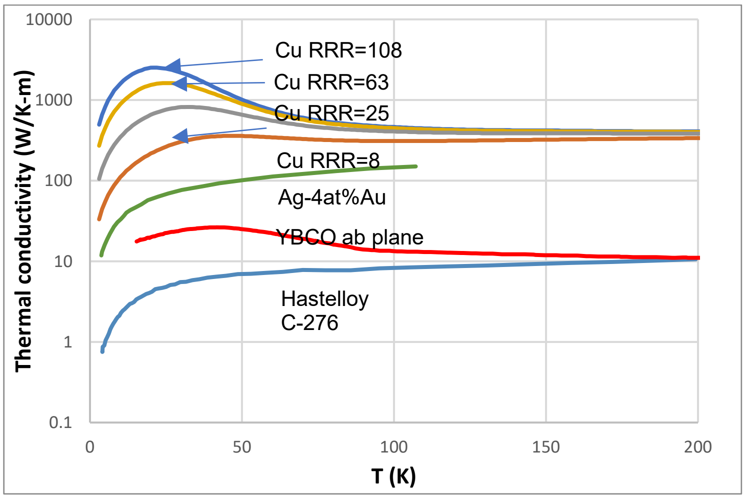

Figure 4. Material thermal conductivity data. Thermal conductivity of Cu was calculated by an empirical formula in [9]; that of Ag-4at%Au was reproduced from [10]; that of Hastelloy C-276 was reproduced from [11]; and that of YBCO in its *ab* plane was reproduced from [12].

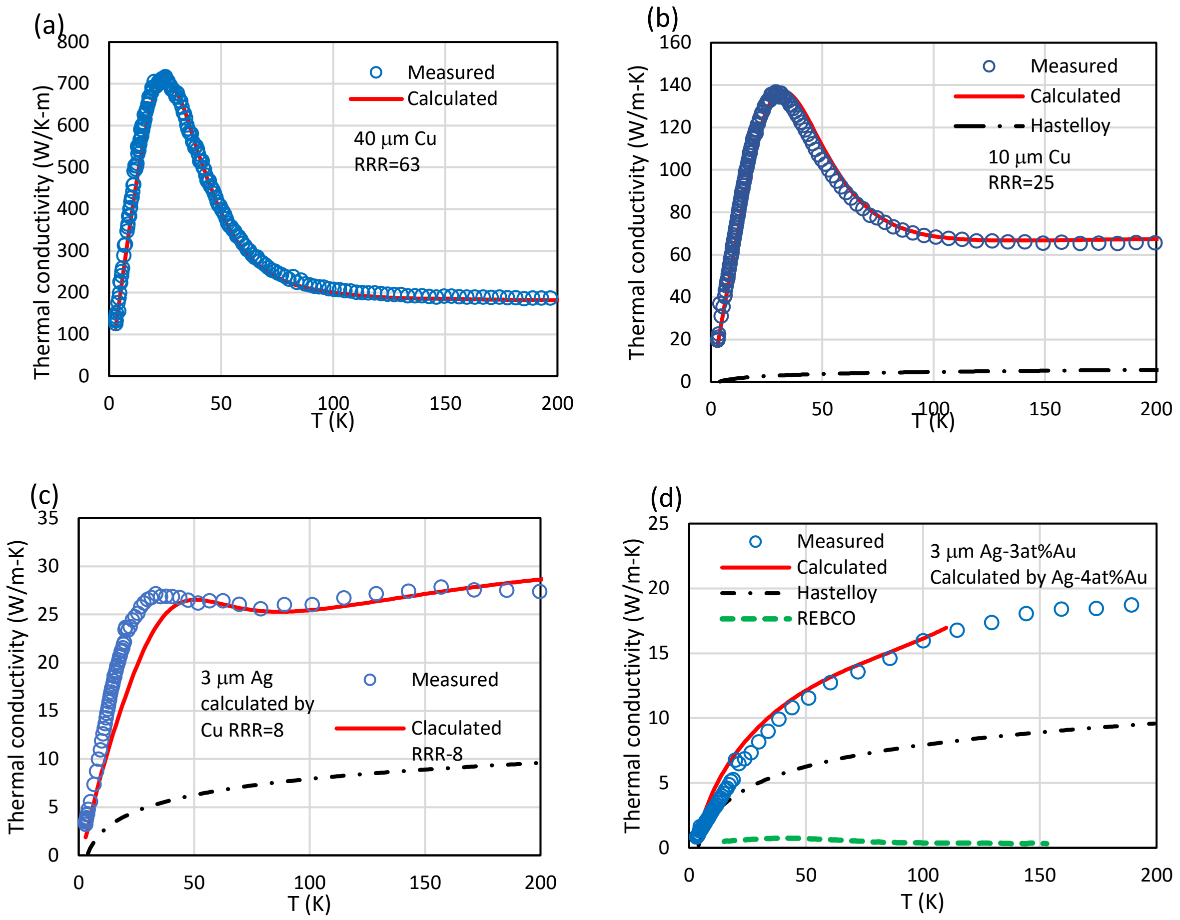

Figure 5. Comparison of measured and simulated thermal conductivity. (a) the sample with 40 μm Cu of RRR = 63. The contributions from Hastelloy substrate are negligibly small, therefore, not shown. (b) REBCO with 10 μm Cu of RRR = 25, the contribution of Hastelloy cannot be disregarded. (c) REBCO with 3 μm Ag stabilizer. The simulation uses data for Cu of RRR = 8, (d) REBCO with 3 μm Ag-3at%Au. The simulated curve uses data for Ag-4at%Au in Ref. [10].

The comparison between experimental $\kappa(T)$ curves and the simulated ones are shown in Figure. 6. In cases of samples with 100 or 40 μm Cu stabilizer (Figure 5(a)), the agreement between the two is very good. The contribution of Hastelloy is negligibly small, therefore is not plotted. For the sample with 10 μm Cu, as shown in Figure 5(b) the agreement is still good but with a small but noticeable contribution from the Hastelloy substrate. For the sample with a 3 μm Ag stabilizer (Figure 5(c)), the contribution from the Hastelloy substrate is significantly more pronounced. Due to the lack of Ag data in the literature, we attempted to use $\kappa(T)$ data of Cu (RRR = 8) for the simulation considering the similarity of thermal conductivity behavior between Cu and Ag. Understandably the simulation in Figure 5 (c) is less satisfactory. The general feature of simulated curve is comparable with the measured data. However, there is significant discrepancy especially at 30 – 50 K where the simulated peak is shifted to higher temperatures. This is obviously due to the use of Cu data instead of those of Ag. For simulation of the Ag-3at%Au sample, data of Ag-4at%Au [10] from 4 – 100 K were used. It should be noted that even in this case of low total thermal conductivity, the contribution from the superconductor layer is still very low as shown in Figure 5(d). Given the appreciable uncertainty caused by using data of Ag-4at%Au, the agreement between the measured and the simulated values is reasonably good.

It should be noticed that the RRR values obtained from thermal conductivity simulation are somewhat different from the electrically measured values both shown in Table I. Similar discrepancies were reported by Bonura and Senatore [5] and were attributed to the uncertainty in Cu thermal conductivity by the formula in Ref. [9]. In addition, the nonuniformity in stabilizer thickness across the sample width may contribute to the error in the simulated thermal conductivity.

4. Conclusion

We measured thermal conductivity of REBCO tapes with different stabilizers at temperatures between 4.2 K and 200 K using the thermal transport option of a physical property measurement system (TTO-PPMS). The electrical conductivity of the stabilizers was also characterized by residual-resistance-ratio (RRR) measurements. The measured RRR values are comparable with those obtained from thermal conductivity simulation. Our results showed that the thermal conductivity of REBCO tapes with a Cu stabilizer thicker than 10 μm was dominated by that of the Cu layer. In such cases, the contribution of the 50 μm Hastelloy substrate was negligible. For samples with 3 μm stabilizers intended for current leads applications, Ag-3at%Au stabilizer has significantly lower thermal conductivity than that with a Ag stabilizer. It is concluded that Ag-3at%Au stabilizer is promising for current leads applications where low thermal conductivity is desirable.

5. Acknowledgement

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