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Thermal contact resistance between high-T_c superconductor and copper

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Abstract

The thermal contact resistivity (W_c) through the connection between a high-T_c superconductor and a copper block was measured from 10 to 200 K for various connecting methods using In solder, silver paste, epoxy resin and varnish as adhesives. W_c was measured by a steady state heat flow method and with a three-terminal non-steady state method by which the thermal diffusivity α was also determined simultaneously. It was found that W_c seriously depended on the connecting method and increased with decrease in temperature. The measured W_c values by both steady and non-steady methods were roughly consistent with each other. The proposed three-terminal non-steady state method was proved to be a useful method to determine both α and W_c. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the field of the cryogenic engineering and low temperature physics, the thermal contact resistance (TCR) through the connection between two materials is an important parameter. For applications of high-T_c superconductors as power current leads to a cryocooled superconducting magnet (SCM), for example, it is necessary to electrically connect a high-T_c superconductor with copper leads. In such a case, TCR between them is as important as the thermal conductivity of the high-T_c superconductor itself to estimate the amount and velocity of the heat intrusion in order to avoid the quenching of SCM [1]. In case of applying a standard non-steady state heat flow techniques for the thermal diffusivity α measurement, the TCRs between the thermometer and the sample and between the sample and the heat sink seriously damage the accuracy of the measurements. In this case, TCR results in the time lag of temperature change $T(t)$ of the sample and the determined α tends to be estimated lower than the true one.

The thermal contact resistance is defined by $R_c = \Delta T/Q$ (K/W), where ΔT is the discontinuous temperature difference at the interface of the two materials and Q is the heat power passing through the interface [2]. The thermal contact resistivity W_c can be defined by $W_c = R_c S$ (mm^2 K/W), where S is the contact area. Even if the two materials are connected using a specified adhesive, the $W_c(T)$ value cannot be decided uniquely because $W_c(T)$

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depends on the surface roughness of the interface, the thickness of the adhesive, the mechanical pressure in the connection and so on. W_c increases with decreasing temperature and is usually very small at the room temperature [2]. Therefore, there is not so much investigation concerning $W_c(T)$ except for the Kapitza resistance at very low temperatures [3].

In this paper, we measured the thermal contact resistivity W_c between the $YBa_2Cu_3O_7$ polycrystal (YBCO) and the copper metal by steady state method between 10 and 200 K for several connecting methods. We also estimated W_c by the three-terminal non-steady state method previously proposed by us [4], in which the thermal diffusivity α is simultaneously determined. The W_c values obtained by both methods were compared each other.

2. Experimental

Fig. 1 shows an experimental setup around the sample for the determination of W_c. YBCO ($T_c = 92$ K, $d = 5.80$ g/cm^3) and the copper block, both of which were situated on the cold stage of the GM cycle helium refrigerator, were connected using various adhesives (silver paste (DUPONT 4922N), In solder (99.9999% purity), epoxy resin (Stycast: 2850-GT) and varnish (GE-7031)). The connecting surfaces were polished using a #1000 emery paper and were rinsed out. The thickness of the used adhesive was estimated to be as thick as ~100 μm. AuFe(0.07 at.%)–chromel thermocouples with 76 μm ϕ in diameter were used to monitor the temperatures at P_1, P_2 and P_3 which were attached using the silver paste [5]. The whole sample chamber was evacuated to $<10^{-5}$ Torr to prevent heat leak by remnant gas. With the continuous heat power Q applied to the slender YBCO sample ($2.5 \times 3.0 \times 30.0$ mm^3), the temperature jump ΔT at the interface was estimated by the extrapolation from the temperature rises at P_1, P_2 and P_3 in the steady state.

3. Results and discussion

Fig. 2 shows a flow chart for the simultaneous determination of the thermal contact resistivity W_c and the thermal diffusivity α using the three-terminal non-steady state method [4]. When a heat

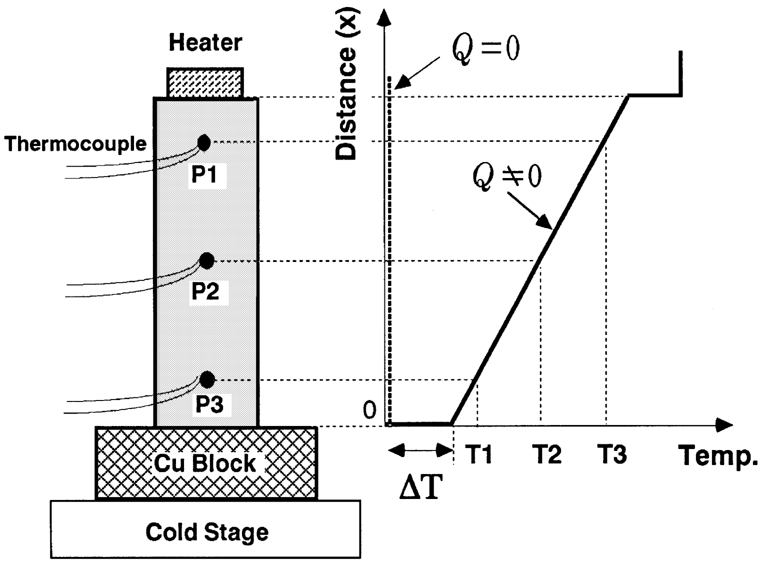

Fig. 1. The schematic view of the experimental setup for the determination of the thermal contact resistivity W_c. The temperature profile in the steady state heat flow method is also shown.

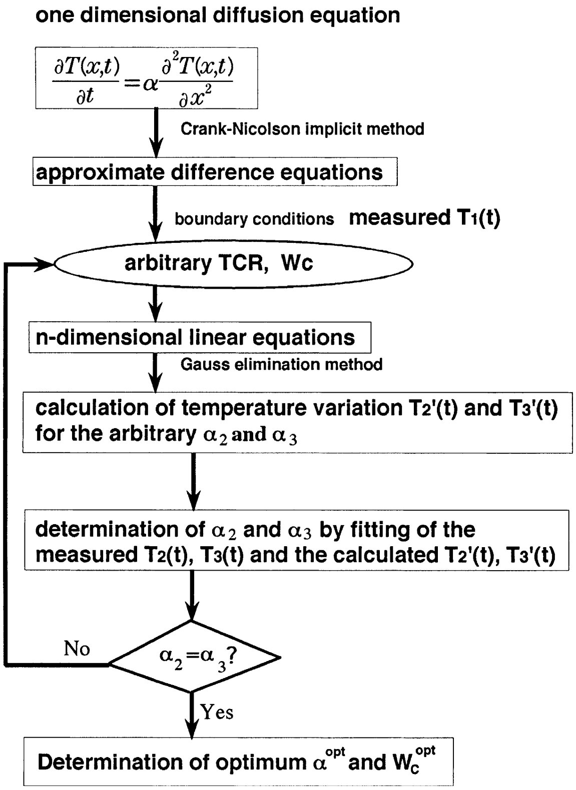

Fig. 2. A flow chart of the simultaneous determination of the optimum thermal contact resistivity W_c^{opt} and thermal diffusivity α^{opt} using the three-terminal non-steady state method.

pulse is applied from a heater into a sample under the identical experimental setup in Fig. 1, the time variation of temperature $T(x,t)$ is described by the one-dimensional diffusion equation. For a certain fixed temperature of the cold stage, the temperature changes $T_1(t)$, $T_2(t)$ and $T_3(t)$ at three measuring points were recorded 14 times/s after applying the heat pulse. The observed temperature rise $\Delta T_2(t)$ at P_2 and $\Delta T_3(t)$ at P_3 were reduced by the maximum value ($\Delta T_{2\,max}$ and $\Delta T_{3\,max}$) and the rising part of the $\Delta T_2(t)$ and $\Delta T_3(t)$ curves was compared with the solutions of the diffusion equation, $\Delta T_2'(t)$ and $\Delta T_3'(t)$. For a fixed contact resistance value W_c, the calculations were performed using $T_1(t)$ as the boundary conditions for various diffusivity values α_2 and α_3. α_2 and α_3, which correspond to the diffusivities of the sample monitored at points P_2 and P_3, were determined from the minimum squared time error $\langle \Delta t \rangle^2$ between the measured and the calculated ones. This procedure was successively performed for various W_c values until the α_2 and α_3 values agreed with each other and the optimum α^{opt} and W_c^{opt} were determined. The fundamental concept of this method is that the thermal diffusivity of a material must be unique even if it is monitored at different points of a sample.

Fig. 3 shows the temperature dependence of the thermal contact resistivity W_c for various connecting methods which was determined by a steady state method. The W_c values seriously depended on the connecting method; the order of W_c values using the various adhesives was GE-varnish > Stycast > In solder > Ag-paste. This order of the magnitude in W_c is consistent with that of the thermal resistivities ($= 1/\kappa$) of the adhesives. For example, the thermal conductivity κ of In metal, Stycast (2850-GT) and varnish (GE-7031) is 780, 15 and 4 mW/cm K at 300 K, respectively. The measured W_c values may include the thermal resistivity of the adhesives besides the intrinsic W_c. The W_c increase with decreasing temperature was gradual in the high temperature regime and became very steep at lower temperatures below ~40 K.

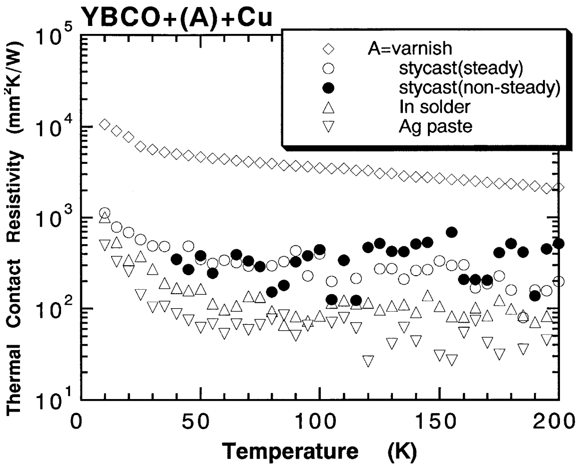

Fig. 3. The temperature dependence of the thermal contact resistivity $W_c(T)$ for various connecting methods which was determined by a steady state method. W_c determined by the non-steady state method was also plotted in the case of Stycast (2850-GT) adhesive.

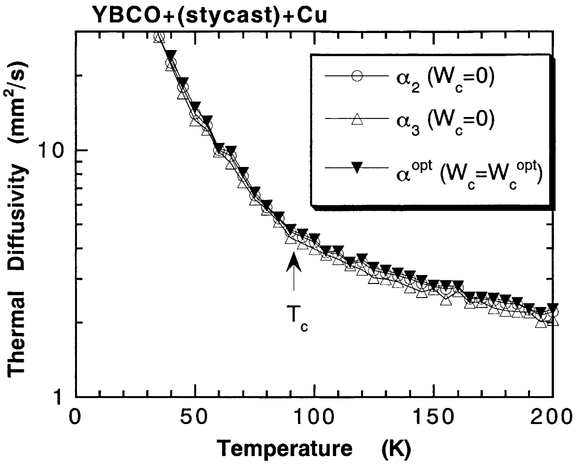

Fig. 4. The temperature dependence of the thermal diffusivities α_2 and α_3 ($W_c = 0$) and the optimum α^{opt} ($W_c = W_c^{opt}$) for the connection using Stycast (2850-GT).

Fig. 4 shows the temperature dependence of the thermal diffusivities α_2, α_3 (in case of $W_c = 0$) and the optimum α^{opt} which was determined simultaneously with the optimum thermal contact resistivity W_c^{opt} for the connection using Stycast (2850-GT). The thermal diffusivity α_2 ($W_c = 0$) estimated at P_2 is always larger than α_3 ($W_c = 0$) estimated at P_3 because the influence of W_c on the α estimation is more reduced for the measuring point separated further from the contact interface. The corrected α^{opt} under the condition of $\alpha_2 = \alpha_3$ using an optimum W_c^{opt} should more precisely reproduce the true value of diffusivity. W_c^{opt} determined by this technique was also plotted in Fig. 3. The W_c^{opt} values are nearly consistent with those determined by steady state method. However, W_c^{opt} cannot be estimated at $T < 40$ K because the thermal diffusivities (α_2, α_3) and the W_c values are too large and are out of the validity limit of the refinement process shown in Fig. 2.

In summary, the thermal contact resistivity $W_c(T)$ at the connection of a high-T_c superconductor and a copper block was measured by both the steady state method and the non-steady state method proposed by us. The W_c values estimated by both methods are nearly consistent with each other. The observed W_c values may include the effect of the thermal resistivity ($= 1/\kappa$) of the adhesive materials besides the intrinsic thermal contact resistivity. In the industrial applications and the basic thermal researches at low temperatures, the quantitative measurement of the thermal contact resistivity for several connections is important, which should be investigated more systematically in the future.

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