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THERMAL RESISTANCE ACROSS A COPPER/KAPTON/COPPER INTERFACE AT CRYOGENIC TEMPERATURES

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ABSTRACT

The high- T_c superconductor current lead heat intercept connection, which is utilized as a thermal intercept to remove the Joule heat from the upper stage lead to a heat sink operating at 50 - 77 K, consists of a structure where a 152- μm film is sandwiched between two concentric copper cylinders. The material chosen for the insulating film is Kapton MT,^{*} a composite film which has a relatively low thermal resistance, but yet a high voltage standoff capability. Here, the measured thermal conductance of a copper/Kapton MT/copper junction in a flat-plate geometry is compared to the results obtained from the actual heat intercept connection. Increasing the contact pressure reduces the thermal resistance to a minimum value determined by the film conduction resistance. A comparison between the resistance of the copper/Kapton MT/copper junction and a copper/G-10/copper junction demonstrates that the Kapton MT layer yields a lower thermal resistance while still providing adequate electrical isolation.

INTRODUCTION

Thermal contact resistance arises in the region of contact where two solid specimens are pressed together. It has long been realized that surfaces are rough on a microscopic scale, which causes the real contact area to be significantly smaller compared to the nominal contact area.¹ Interstitial materials may be deliberately introduced in order to control the thermal contact conductance (h_c), $h_c = q/\Delta T$, where q and ΔT are the heat flux and the temperature drop across the interface respectively. To enhance h_c , the bare metal surfaces may also be coated with soft metals of high thermal conductivity by electroplating or vacuum deposition.² The insert's thermal conductivity and hardness, relative to the values of the corresponding properties of the base materials forming the contact, together with the insert's thickness, dictate the resulting change in h_c .

MASTER

^{*} Kapton MT is a registered trademark of DuPont Films.

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The high- T_c superconductor current lead heat intercept connection designed by Argonne National Laboratory and Superconductivity, Inc. consists of a structure where two concentric copper cylinders are separated by a composite (Kapton MT) film. As the purpose of the heat intercept connection is to efficiently transfer the heat generated in the copper portion of the current lead, plus that conducted in from the ambient, away from the low-temperature superconductor magnet, it is imperative that the total thermal resistance of the heat intercept connection in the radial direction be kept as small as possible. At the same time, electrical isolation must be maintained between the inner and outer copper cylinders, necessitating the use of an electrically insulating interstitial material. It was determined previously that h_c at the interface between the two copper cylinders, separated by a thin-walled G-10 tube, provided the largest component of the total thermal resistance.³ Therefore, in the most recent design, the G-10 tube is replaced with a thin Kapton film which, while still providing electrical isolation, is softer than G-10 and has a higher thermal conductivity, offering the potential for a reduced $R_c (=1/h_c)$ and thus a lower total thermal resistance. Detailed descriptions of previous versions of the heat intercept connection are given elsewhere.⁴

Measuring h_c in a cylindrical geometry is relatively difficult. Because the contact pressure in a cylindrical joint is dependent on the initial interference and the differential expansion of the two cylinders, which is a function of radial heat flux, it is implicit and not readily controllable.⁵ Furthermore, the cylindrical surfaces also involve other characteristics such as out-of-roundness, in addition to parameters like surface roughness and waviness that are important in flat junctions. Due to these complexities in the cylindrical geometry, the present work concentrates on the measurement of the thermal resistance of a copper/Kapton MT/copper interface in a flat-plate geometry at cryogenic temperatures, and correlates these results with the limited data available from the thermal performance of the actual heat intercept connection. The effects of the contact pressure and the operating temperature on the thermal resistance are also evaluated.

HEAT INTERCEPT CONNECTION

A schematic diagram of the cross-section of the high- T_c superconductor current lead heat intercept connection is presented in Fig. 1. The heat intercept connection is primarily a thermal intercept to remove the Joule heat from the upper stage lead to a heat sink operating at 50 - 77 K, but also electrically isolates the leads from the high temperature superconductor (HTS) elements mounted in the central hole. A 152- μm film is sandwiched between the two concentric ETP copper cylinders, the inner disk and the outer ring. The outer ring is in the shape of a square, with a circular hole.

The material chosen for the insulating film is Kapton MT, a polyimide film with aluminum particles as a filler, giving it a relatively low thermal resistance, but yet a high voltage standoff capability. The thermal conductivity of this material at cryogenic temperatures is sufficient to result in a small temperature drop across the sheet at the desired heat flux input, while the high dielectric strength of Kapton MT (114 V/ μm) allows only a thin layer to be used. The Kapton sheet is wrapped snugly around the inner disk with a double wrap. Its outside edge is sealed to the underlying layer with GE 7031 varnish, and its ends nearly meet but do not overlap.

The ETP copper disk and ring are cleansed by acid pickling, then treated by 1.27- μm nickel plating and 1.91- μm gold plating in order to reduce h_c across the interface.

Figure 1. Heat intercept connection cross section

The inner disk, the interstitial layers, and the outer ring are held together by means of a thermal-interference fit. The radial interference is measured to be $63.5 \mu\text{m}$, which results in a calculated contact pressure of 110.3 MPa at room temperature. The amount of interference dictates the radial contact pressure on the joint which affects the overall thermal resistance.

A heater is mounted in the center of the inner disk to simulate the Joule heat generated by the current lead, while the outer ring is thermally connected to a heat sink. The resulting radial heat flux is approximately uniformly outward.

The experimental apparatus is operated under vacuum conditions. Temperatures are measured by silicon diodes mounted as shown in Fig. 1.

FLAT-PLATE GEOMETRY EXPERIMENTAL APPARATUS

Due to the relative difficulties in controlling and measuring the contact pressure, as well as the additional surface characteristics such as out-of-roundness, only limited data are available for the thermal performance of the actual cylindrical heat intercept connection. Therefore, a flat-plate geometry consisting of a copper/Kapton MT/copper junction is investigated instead.

The test system illustrated in Fig. 2 consists of two samples, upper and lower, and two calibrated heat flux meters which are pressed together and aligned to the center line of the apparatus. The test specimens are ETP copper, coated identically as the copper pieces in the actual heat intercept connection. The interstitial material is two layers of Kapton MT which are glued together by GE 7031 varnish and allowed to dry.

The surface treatments and roughnesses of the components in the test column, as well as the thickness of the interstitial material, are tabulated in Table 1, which provides a comparison with those in the actual heat intercept connection shown in Fig. 1 and the heat intercept connection containing a G-10 tube.³

The thermal conductivity of the heat flux meters was previously calibrated against a reference 304SS bar obtained from the National Institute of Science and Technology. The temperature drops along the heat flux meters and across the sample interface are measured by differential Type E thermocouples. The differential thermocouples are calibrated at a single point by immersing one junction into liquid nitrogen and the other into an ice bath, and applying the resulting percent deviation from the standard table to all measurements. The silicon diodes mounted on the copper heat mounts are utilized as the reference temperatures for the differential thermocouples. The thermocouples are inserted into

Figure 2. Schematic diagram of the flat-plate geometry experimental apparatus

51- μ m diameter holes drilled to the center lines of the samples and heat flux meters, and which are partially filled with fine copper powder in order to provide reliable thermal contact.

Indium foil is inserted at all junctions besides the sample interface in order to reduce extraneous contact resistance. Two thermal shields are placed above and below the heat flux meters in order to reduce the radiation heat transfer. The entire test column is surrounded by a thermal shield to minimize radiation gain from the ambient.

Before each experiment, a small amount of initial pre-stress is applied to the samples via a loading screw mechanism to guarantee a good contact. The pre-pressure, which has a magnitude of 0.809 MPa around room temperature, reduces to 0.007 MPa at 123 K and vanishes below 100 K. In order to apply and control the contact pressure at cryogenic temperatures, a bellows located below the lower ball bearing is pressurized with helium gas to obtain an evenly distributed pressure, which is measured by a load cell.

The outputs of the thermocouples, silicon diodes, and the load cell amplifier are monitored and recorded by a Macintosh PowerPC computer, then simultaneously converted and analyzed by a labVIEW control program. If the temperature drops across the sample interface as well as the upper and lower heat flux meters are all within a set criterion for the last 50 data points, the system is considered to be in steady state. Starting with the reference silicon diodes located on the copper heat mounts, each temperature point is calculated sequentially from the differential thermocouple readings. The temperature drop at the sample interface is over-determined by the calculation downwards and upwards, which are averaged to determine the final ΔT . The heat flux at the sample interface is considered as the average of the upper and lower heat flux meters.

All measurements are conducted under a vacuum condition of 6.5×10^{-5} torr on average, which is measured by a cold cathode vacuum gauge.

Table 1. Surface treatments and roughnesses of the components in the three joints

Flat-Plate Geometry Experimental Apparatus		
Component	Surface Treatment	Surface Roughness (μm)
ETP Copper Upper Sample	Nickel, Gold Plate	3.575
Kapton MT Sheet (185 μm)	none	0.390
ETP Copper Lower Sample	Nickel, Gold Plate	0.994
Heat Intercept Connection Using G-10 as Interstitial Material		
Component	Surface Treatment	Surface Roughness (μm)
Cu Inner Disk	Grind, Gold Plate	0.254 (before plating)
G-10CR Tube (381 μm)	none	1.676(inner)/1.981(outer)
Cu Outer Ring	Grind, Gold Plate	0.254 (before plating)
Heat Intercept Connection Using Kapton MT as Interstitial Material		
Component	Surface Treatment	Surface Roughness (μm)
ETP Copper Inner Plug	Nickel, Gold Plate	0.813 (before plating)
Kapton MT Sheet (152 μm)	none	0.390
ETP Copper Outer Ring	Nickel, Gold Plate	0.813 (before plating)

UNCERTAINTY ANALYSIS

The total experimental uncertainty in the thermal contact conductance, u_h , is calculated from

$$u_h = \sqrt{\left(\frac{u_q}{\Delta T}\right)^2 + \left(\frac{q u_{\Delta T}}{(\Delta T)^2}\right)^2} \quad (1)$$

where u_q and $u_{\Delta T}$ are the uncertainties in q and ΔT respectively. Since q is the average of the measurements of the upper and lower heat flux meters, u_q is reduced to $\frac{1}{2}(u_{q,upper}^2 + u_{q,lower}^2)^{1/2}$ where $u_{q,upper}$ and $u_{q,lower}$ are the uncertainties in q from the upper and lower heat flux meters, which take the form

$$u_{q,upper/lower} = \sqrt{\left(\frac{u_k \Delta T_q}{L}\right)^2 + \left(\frac{K u_{\Delta T_q}}{L}\right)^2} \quad (2)$$

where L and ΔT_q are the length and the temperature drop across the heat flux meter respectively, and u_k and $u_{\Delta T_q}$ are the uncertainties in the thermal conductivity K of the heat flux meters and the differential thermocouple readings.

We consider the total experimental uncertainty, consisting of bias errors determined by instrument specifications, and precision errors (95% confidence level) caused by scatter in the data.⁶ The term $u_{k,bias}$ is the material variability of the standard reference bar, given as 2% below 100 K, and $u_{\Delta T,bias}$ is the error introduced by the differential thermocouples ($\pm 1\%$). The corresponding uncertainties in h_c , reported in the figures in the form of error bars, are equal to $(u_{h_c,bias}^2 + u_{h_c,precision}^2)^{1/2}$ in which the different errors are treated separately but following the same procedure.

Both junctions of the differential thermocouple positioned across the sample interface are mounted in holes located 2.413 mm from the interface. The resulting

temperature drop across the copper is estimated as 1.4% of the ΔT across the interface and is considered to be negligible.

EXPERIMENTAL RESULTS AND DISCUSSION

Measured values of h_c as a function of the average temperature across the sample interface are presented in Fig. 3. For the Kapton sheet itself, h_c is defined based on its thermal conductivity K :⁷

$$h_c = \frac{K}{\delta} \quad (3)$$

where δ includes the thickness of the GE varnish ($33 \mu\text{m}$), which, together with the thickness of the Kapton layers ($152 \mu\text{m}$ in total) gives $\delta = 185 \mu\text{m}$.

Figure 3 displays the experimental data over an average temperature ranging from 50 K to 120 K. Observe that h_c varies with the contact pressure P , because when the two surfaces are pressed tighter together, the soft Kapton film is squeezed into the voids between the actual contact spots, thus increasing the effective contact area and causing the R_c to diminish. From the well-known correlation for h_c of two contacting randomly rough surfaces⁸

$$\frac{h_c \sigma}{k} = c \left(\frac{P}{H} \right)^n \quad (4)$$

where σ is the surface roughness, k the harmonic mean thermal conductivity and H the micro hardness of the softer material in contact, h_c is expected to increase with the contact pressure P . Moreover, the thickness of the Kapton layer probably reduces when it is pressed, therefore decreasing its contribution to the thermal

Figure 3. Effect of contact pressure on thermal contact conductance, as measured in a flat-plate geometry

resistance and resulting in an increased h_c . Presumably, increasing P further would yield a further increase in h_c up to the limit posed by the resistance of the Kapton layer itself. However, $P = 19.65$ MPa represents the maximum allowable pressure in our flat-plate apparatus.

Figure 4 provides a comparison between the two different interstitial materials, G-10 and Kapton MT, which are utilized in the heat intercept connection. The Argonne National Laboratory (ANL) data are experimental results for h_c at the interface between two concentric copper cylinders separated by a thin-walled G-10 tube. The Superconductivity, Inc. (SI) data are for a copper/Kapton MT/copper interface in the geometry shown in Fig. 1. The two sets of experimental data are obtained under comparable q values, 4740 W m^{-2} and 4940 W m^{-2} respectively, but the SI data are at much higher contact pressure ($P = 91$ MPa) while the ANL data are at $P = 43$ MPa around 60 K. The two solid curves represent the contributions to h_c from the Kapton and G-10 layers. In addition to being thinner, the Kapton MT layer has a higher K , resulting in a higher h_c . The Kapton MT layer, which is softer, thinner and of higher K than the G-10 layer, substantially reduces the contact resistance between the Kapton MT and the copper, and subsequently the thermal resistance across the layer itself dominates. However, the thermal contact resistance at the G-10/copper interfaces is quite large, as indicated by the difference between the ANL data and the G-10 curve, which is also due to the relatively lower P . Thus, it is clear that Kapton MT is a better interstitial material compared to G-10, with regard to enhancing h_c while still providing adequate electrical isolation.

Compared with the h_c data obtained from the flat-plate geometry experimental apparatus presented in Fig. 3, the h_c results are consistent in that at the much higher P for the SI data, h_c increases to its limiting value determined by the Kapton MT resistance.

Figure 4. Comparison between the different interstitial materials, G-10 and Kapton MT, as measured in a cylindrical geometry.

CONCLUSIONS

The thermal contact conductance at a copper/Kapton MT/copper interface is investigated at cryogenic temperatures. The results indicate that increasing the contact pressure increases the contact conductance, in accord with expectations. The thermal resistance of the Kapton MT layer determines the upper limit to the contact conductance. The interstitial film Kapton MT dramatically lowers h_c compared with a thin G-10 layer which is relatively stiffer, thicker, and of lower thermal conductivity. Hence, the Kapton MT film utilized is a better interstitial material in the high- T_c superconductor current lead heat intercept connection, because it provides relatively low thermal contact resistance, but yet sufficient electrical insulation.

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