Millikelvin thermal conductance measurements of compact rigid thermal isolation joints using sapphire-sapphire contacts, and of copper and beryllium-copper demountable thermal contacts.

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We present thermal conductance measurements of different types of bolted joint at sub-Kelvin temperatures. Joints containing sapphire surfaces provided good thermal isolation; the mechanism appears to be the existence of a very small area over which the surfaces are actually in contact. Various configurations were measured at temperatures between 100 mK and 4 K. The best joint contained sapphire discs separated by diamond powder and had a conductance of 0.26 μWK^{-1} (T/1 K)$^{2.9}$, where T is temperature. A mechanical support structure constructed from similar joints, but using alumina powder, had a measured heat leak of 2.57 μW between 80 mK and 1.1 K and was capable of supporting a mass of over 10 kg. Joints between metal surfaces provided good thermal conduction; a bolted joint between copper and a beryllium-copper alloy (C17510 TF00) had a measured conductance of 46 mW K^{-1} at 100 mK, increasing linearly with temperature. Measurements were also made on a copper-copper compression joint using differential thermal contraction to provide the clamping force. The performance was approximately an order of magnitude worse than for the bolted joint. These measurements were all made as part of the development programme for the SCUBA-2 astronomical instrument; the design requirements were achieved for both insulating and conducting joints.

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1. INTRODUCTION

The thermal conduction between two surfaces in contact is often of great importance in cryogenic systems. Since any surface will be rough on a microscopic scale, the surfaces will only actually be in contact over a much smaller area than the nominal contact area. Moreover, if the surfaces are pressed together, they will deform to some extent, resulting in a contact area — and thus conductance — that increases with applied force. Predicting the conductance of a given joint is difficult, and it is therefore usually necessary to rely on experimental data. In this paper we describe measurements we have made in order to optimise two very different types of joint. In one case we wished to maximise the conductance across a joint. In the other we took advantage of the small contact area between hard surfaces in order to obtain thermal isolation.

Both sets of measurements were part of the design programme for the SCUBA-2 astronomical instrument [1]. This instrument has demanding requirements for thermal design, in particular for the sections at temperatures of 1 K and below [2]. One area which has required great care is the design of the detector heat sinks, which operate at a temperature of approximately 50 mK. These components, with a mass of over 6 kg, have to be rigidly supported from the surrounding 1-K radiation shield with an acceptably low heat leak from the shield (less than approximately 2.5 μWK^{-1} between 50 mK and 1.1 K). In addition, motion during cool-down must be negligible (less than 100 μm). The usual solution in similar situations is to use a rigid material with low thermal conductivity and high length to area ratio. Space constraints make such an approach impractical here, even if the thermal contraction of such a material could be tolerated. Compact structures can be constructed using Kevlar® thread in tension [3–6]; however, these are liable to creep over time as well as during thermal cycling. We therefore investigated the use of contact resistance between sapphire surfaces to provide thermal isolation. We present measurements which were made on joints of various designs.

The heat sinks which these thermal isolation structures support are made from a beryllium copper alloy (BeCu), and are connected to the source of cooling (a dilution fridge) by copper thermal links. A demountable joint is required with a conductance greater than 2 mW K^{-1} at a temperature of 50 mK. Results are available in the literature for various designs of demountable joint [7–19], but none of these designs were suitable for this application. In particular, we are not aware of any previous measurements on contact to beryllium copper. We carried out measurements on a bolted joint between copper and beryllium-copper, as well as on a compression joint between two copper surfaces.

Most previous measurements on thermal contacts for use at these temperatures consist of electrical resistance measurements made at a temperature of 4.2 K [13, 20]; the thermal conduction at lower temperatures is then calculated from the results. We measured the thermal conductance directly at temperatures below 1 K.

2. THERMAL ISOLATION JOINTS

A. Measurements and samples

In order to find an acceptable design for a thermal isolation joint, measurements were made using various configurations.

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Configuration	Composition[a] of *one* joint in the sample	Powder	Temp. range	Applied torque (N cm)	Screws[b]	Calculated clamping clamping force (N)	Joint area (mm^2)
1	Cu-S-Cu		mK	8	4 × M2	800	80
2a	Cu-p-S-p-Cu	110μm alumina	mK	8	4 × M2	800	80
2a	Cu-p-S-p-Cu	110μm alumina	$>$ 2K	8	4 × M2	800	80
2b	Cu-p-S-p-Cu[c]	110μm alumina	mK	8	4 × M2	800	80
2c	Cu-p-S-p-Cu	110μm alumina	$>$ 2K	15	4 × M3	1000	20
2d	Cu-p-S-p-Cu	110μm alumina	mK	16	4 × M2	1600	80
3a	Cu-S-p-S-Cu	110μm alumina	$>$ 2K	15	4 × M3	1000	20
3b	Cu-S-p-S-Cu	110μm alumina	$>$ 2K	15	4 × M3	1000	80
3c	Cu-S-p-S-Cu	110μm alumina	mK	7	3 × M2	525	80
4	Cu-S-Sball-Cu[d]		mK	8	4 × M2	800	
5a	Cu-S-p-S-Cu	30μm diamond	$>$ 2K	10	4 × M3	700	80
5b	Cu-S-p-S-Cu	30μm diamond	$>$ 2K	15	4 × M3	1000	80
5c	Cu-S-p-S-Cu	30μm diamond	$>$ 2K	20	4 × M3	1300	80
5d	Cu-S-p-S-Cu	15μm diamond	$>$ 2K	10	4 × M3	700	80

[a] Cu: copper, S: sapphire disc, Sball: sapphire ball, p: powder

[b] Stainless steel screws were used, apart from configuration 3c which used brass screws.

[c] As configuration 2a, but with 50% less powder

[d] One half of the sample was a joint as configuration 2a

Table I: Details of the sapphire isolation joint sample configurations

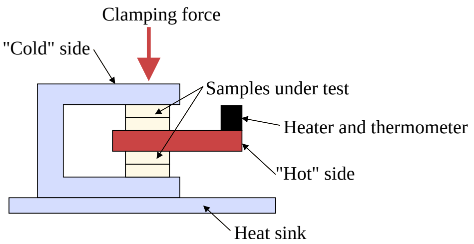

Figure 1: Configuration of the sapphire thermal isolation joint conductance measurements. Each sample consists of two joints with the conduction path in parallel.

For each joint, thermal isolation was achieved either at the boundary between a piece of sapphire and a piece of copper, or between two sapphire pieces. Since sapphire is very hard, deformation under pressure should be minimal, leading to a very small actual contact area at the interface. Each sample necessarily consisted of two such joints with the conduction path in parallel, enabling a clamping force to be applied without providing an additional thermal path across the joints (see Fig. 1).

For most samples, powder was used between the contacting surfaces in order to decrease contact conductance [21]. The samples differed in various respects including the powder material and size, clamping force, diameter of the sapphire surfaces and whether one or two pieces of sapphire were used in each joint. Details are given in Table I. The screws were tightened using a torque driver with a nominal accuracy of $\pm 5\%$; an approximate value for the contact force can be calculated from the torque and screw size [22], and is shown in the table for each configuration. The joint surfaces were kept perpendicular by keeping a similar pressure on all the screws as they were tightened.

The sapphire discs[1] had a thickness of approximately 1 mm, a surface roughness of 0.1 μm per inch, and were uncoated. The copper surfaces were left as machined. Before assembly, sapphire and copper pieces were degreased by cleaning them with acetone in an ultrasound bath followed by rinsing in propanol. Where powder was used, a sufficient quantity to ensure approximately 60% coverage of the sapphire discs was applied. This presumably results in a powder layer with a thickness of approximately the diameter of the powder grains.

Several thermal conductance measurements were carried out between 100 mK and 4.2 K in an ADR system. Having established that the conductance of all joints measured followed a similar temperature power-law, the majority of subsequent measurements were made at temperatures near 2 K and 4.2 K in a pumped helium cryostat. The calculated error in the conductance measurements is approximately $\pm$ 3%.

Conductance measurements were made by applying heat to one side of the joint using a resistor and measuring the resulting temperature rise with a ruthenium oxide[2] or neutron transmutation doped (NTD) [23, 24] germanium thermistor,[3] monitored by a resistance bridge.

B. Results and discussion

The conductance of the samples measured between 100 mK and 4.2 K could be fitted well by a power-law with coefficients between 2.3 and 2.5. For samples measured only near

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[1] Sold for use as optical windows by Edmund Optics Inc., Tudor House, Lysander Close, York, UK

[2] Scientific Instruments, Inc. West Palm Beach, Florida, USA

[3] Haller-Beeman Associates, Inc., 5020 Santa Rita Rd., El Sobrante, CA, USA

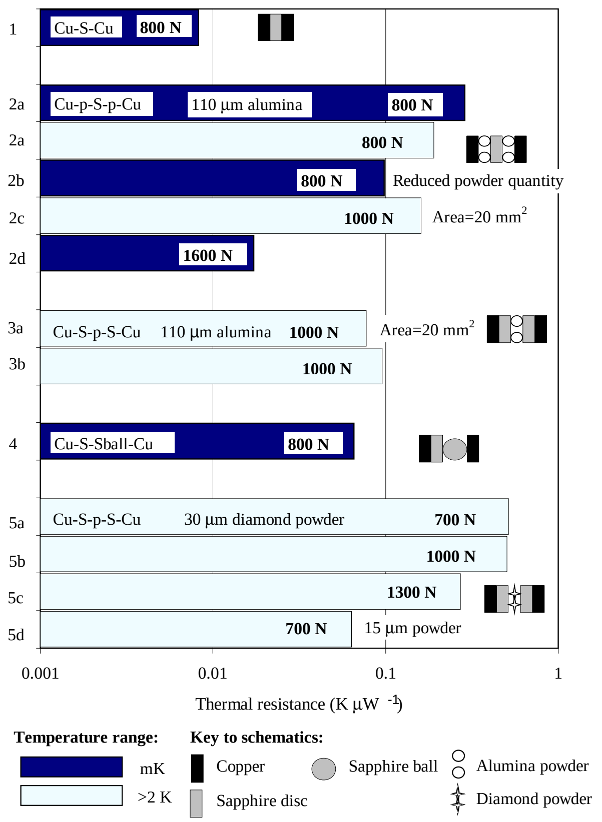

Figure 2: Measured thermal resistance at 2 K for the different sapphire thermal isolation joint measurements. These values are for complete samples consisting of two joints conducting in parallel, as shown in Fig 1. It should be noted that a logarithmic scale is used for the x axis. The configuration for each measurement is shown on the y axis; more information on each configuration is given in Table I.

2 K and 4.2 K, assuming a power-law dependence produced coefficients between 2.6 and 2.9, and therefore in reasonable agreement. It is therefore sufficient to compare the properties of samples at temperatures above 2 K, without the inconvenience of measuring each sample at millikelvin temperatures. The resulting thermal resistance values at 2 K are summarised in Fig. 2. The best (lowest conductance) joint was sample 5a, with a conductance of 0.26 μWK^{-1} (T/1 K)$^{2.9}$, where T is temperature.

The results present a consistent picture. It is true that many more measurements would have been required in order to be certain that sample to sample variations were not significant, though the good agreement for the one configuration measured twice (2a) is encouraging.

It is clear that the bulk thermal resistance of the samples is not significant. While sapphire is a reasonably poor conductor below 1 K, it can be seen from Fig. 3 that the bulk conductance values are many orders of magnitude higher than the conductance of each of the samples measured. The large resistance variation between samples (nearly three orders of magnitude at 50 mK), all of which have similar quantities of bulk sapphire, also suggests that the thermal impedance is almost entirely at the interfaces.

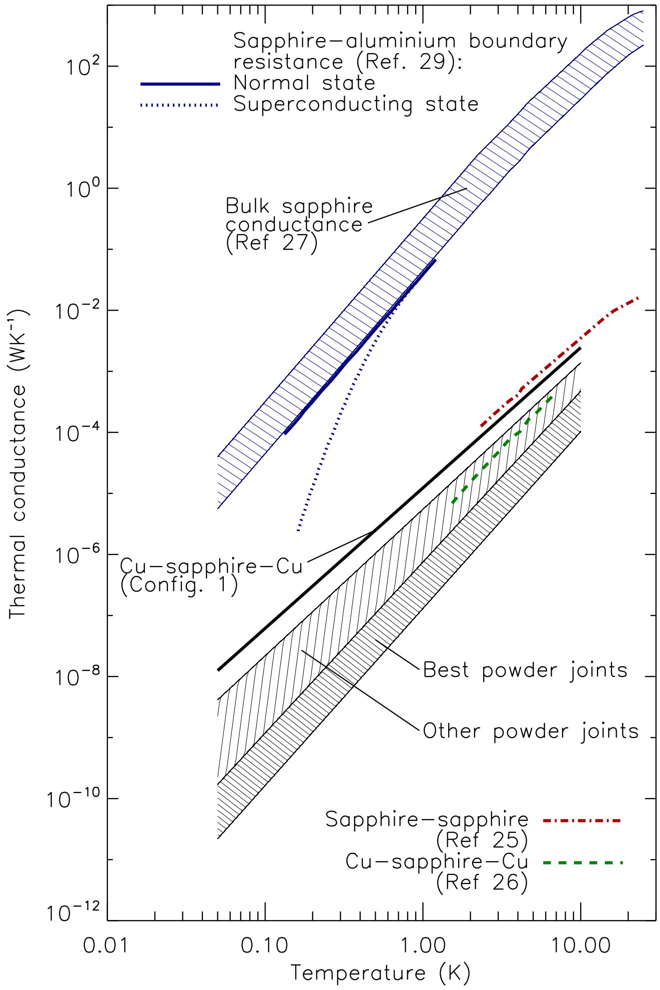

Figure 3: Measured conductance values for the thermal isolation joints. The values shown are the conductance for a single joint, not the two joints in parallel making up one sample. The range labelled “best powder joints” excludes configurations 2d (high clamping pressure), 3a (small nominal contact area), 4 (sapphire ball sample) and 5d (small powder size). For comparison, measurements on a sapphire-sapphire joint [25] and on a copper-sapphire-joint [26] are also shown. In addition, the expected bulk conductance through a 1 mm thickness and 10 mm diameter sapphire disc, as used in the contact samples, is shown. The conductivity of sapphire depends not only on the crystal structure but on the size of the sample measured and the surface roughness; here a range of values from the literature is shown [27]. These measurements were made down to a temperature of 2 K, and have been extrapolated to lower temperatures by assuming a T^3 temperature dependence. This is predicted by theory, and has been confirmed by several measurements at temperatures down to 100 mK [28–30]. Measured values for the acoustic boundary resistance between sapphire and aluminium [29] (both in the normal and superconducting state) are also shown, scaled for a contact area with 10 mm diameter. These have been divided by two to allow for the interface at each side of the sapphire discs.

The bulk powder thermal resistance should also be small. We cannot calculate a precise value for the alumina powder, since we are not aware of any conductivity measurements on alumina *powder*, and different reported measurements on bulk alumina differ by more than an order of magnitude. However, taking values from Ref. [28] as a lower limit on conductivity, and approximating the powder as a single partial layer of spherical grains, we obtain a bulk conductance of approximately 10 mW K^{-1} $(\mathrm{T}/1\ \mathrm{K})^{2.7}$ at temperature T. The true conductance would therefore have to be over three orders of magnitude lower than this estimate for the bulk powder conductance even to compare with the overall conductance of the highest conductance samples. The fact that samples with similar amounts of powder show a large variation in resistance also suggests that the bulk thermal resistivity of the powder is not dominating the results.

There are two likely causes for the boundary resistance. Firstly, as with any contact, the true contact area will be smaller than the nominal area. Secondly, at these temperatures there will be a boundary resistance between two dissimilar materials even in perfect physical contact, due to acoustic mismatch [31] (sometimes referred to as Kapitza resistance). However, this second mechanism does not seem to be significant for our samples, for the following reasons. Figure 3 shows measured conductance values for the acoustic boundary resistance between sapphire and monocrystalline aluminium [29]; these were in good agreement with theoretical predictions. Making the assumption that the values for sapphire and polycrystalline copper have a similar order of magnitude to this, we can see that the acoustic mismatch conductance is many orders of magnitude larger than the total conductance of our samples.

Further evidence comes from the two sets of measurements made on joints which were similar, but with nominal surface areas differing by a factor of four (configurations 2a & 2c, and 3a & 3b). If acoustic mismatch was the dominant mechanism, the conductance should simply increase linearly with nominal contact area, and thus differ by a factor of four. Instead, there was little change, with the conductance increasing slightly (and thus the resistance decreasing) as the area was *reduced*.

This is plausible if the boundary resistance is dominated by a small true contact area, and is consistent with the true contact area remaining approximately constant as the nominal area changes. This is the case for metallic contacts; theory and experiment for room temperature joints [33] as well as low temperature measurements [34] suggest that the reduction in nominal area is compensated for by an increase in the proportion of true to nominal contact area caused by greater deformation due to the increased pressure. This does of course mean that it is not useful to compare different joints in terms of conductance per unit area.

For joints with alumina or diamond powder, increasing contact pressure while keeping the nominal contact area constant increased the thermal conductance (configurations 2a and 2d, and 5a-c). This also agrees with many observations on metallic contacts, as well as measurements on sapphire [32] and is presumably again related to an increase in true contact area. The dominant mechanism for the high thermal resistance of our samples thus appears to be a small actual contact area.

All configurations with powder between the surfaces had a lower conductance than configuration 1, which did not contain powder. While the use of powder is clearly beneficial, it is not clear from these results whether the effect of powder is merely to reduce the area of direct contact between the surfaces, or whether the thermal paths between the surfaces actually pass through a small number of grains, possibly through several grains in series. It was observed that reducing the amount of alumina powder (configuration 2b) reduced the resistance considerably, as did reducing the size of diamond powder (configuration 5d).

The conductance for joints with diamond powder (configuration 5) was generally lower than for alumina powder, despite the diamond grains being much smaller. This is presumably because diamond, being harder than sapphire, deforms less under pressure.

One sample was measured in which one of the joints consisted of a sapphire ball in contact with a sapphire plate (configuration 4). Such a joint should have a very low macroscopic contact area. However, the pressure at the contact will be correspondingly higher, potentially leading to more deformation. In fact, the conductance seems no better than the other joints, and this concept was not pursued further.

Finally, one might expect joints consisting of contact between two sapphire surfaces (configurations 3-5) to have lower conductance values than those only with contact between sapphire and copper (configurations 1 and 2), since a copper surface can deform easily to match the shape of the sapphire surface. However, it is not clear from these measurements if this is indeed the case.

We are aware of three other sets of measurements similar to ours [25, 26, 32]. The power-law coefficients in these measurements were similar those found by us. Measurements on a copper-sapphire-copper joint [26] with an unknown contact force (Fig. 3) show a similar but somewhat lower conductance than our equivalent sample (configuration 1).

As with our measurements, the results from Ref. [32] showed that the use of alumina powder decreased the conductance considerably. Unfortunately, the results are quoted only in terms of conductance per unit area, and the area of their samples is not given. If our results are also converted to conductance per unit area, we find that their copper-sapphire-copper and sapphire-powder-sapphire joints have approximately an order of magnitude lower conductance than our copper-sapphire-copper (configuration 1) and best sapphire-powder-sapphire (configuration 5a) joints respectively. However, since we have shown that the conductance does not scale with area, such a comparison is spurious unless their samples had a similar nominal cross-section to ours.

Results from Ref. [25] for a sapphire-sapphire joint with no powder (a configuration not measured by us) show a very similar conductance to our copper-sapphire-copper joint (configuration 1). The area of their joint is not given, but as with bare metal joints, the conductance of a sapphire joint without powder is likely not to depend strongly on area.

Given the differences between the samples described above and those measured by us, these results all appear to be consistent with our measurements.

Finally, it should be noted that unlike all the samples discussed here, it is possible to make *permanent* bonds between sapphire surfaces that result in a very highly conducting joint [35].

C. Chosen design

These results were used to design a joint which met our requirements, based on configuration 3b. This is shown in Table I as configuration 3c. Alumina powder was used despite the better performance of joints using diamond powder, due to concerns that using diamond might cause the sapphire to fracture on repeated thermal cycles since it is harder than the sapphire.

An individual isolation unit is shown in Fig. 4. Two copper pieces, one “U” shaped and the other with a tongue, are pressed together with a sapphire-powder-sapphire joint providing isolation above and below the tongue. A sufficient quantity of powder is used to ensure approximately 60% coverage of the sapphire discs.

A problem with the individual isolation joints is that in principle they are free to rotate in two degrees of freedom (in practise, the hot and cold sides of the joint rotate against each other but are remarkably resistant to being pulled apart). In a full support, four isolation units are set at an angle of 45 degrees to each other in order to provide a support which has no degrees of freedom.

A prototype support was constructed using four joints in this manner. The measured total heat leak for a cold end temperature of 80 mK and different temperatures at the hot end is shown in Fig. 5. A fit is shown, assuming the conductance follows a power-law as found with individual samples. Differentiating this fit gives a conductance of 7.3×10^{-6} (T/1 K)$^{3.2}$ WK^{-1}, and thus with a power-law exponent slightly larger than those measured on individual samples. This expression is also used in Fig. 5 to predict the total power for a cold end temperature of 500 mK instead of 80 mK. It can be seen that changing this temperature has a very small effect on the total power, which is dominated by the thermal conductance at higher temperatures. It is therefore not important that these measurements were made with a lower temperature of 80 mK instead of the specification value of 50 mK; the difference in power for these temperatures is imperceptible.

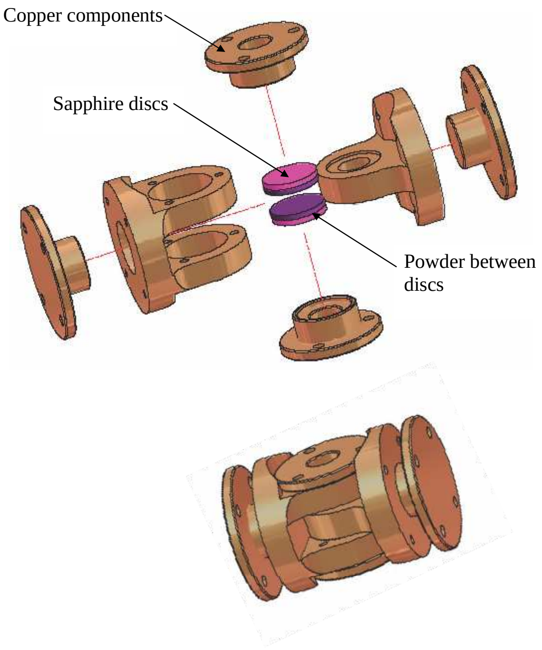

Figure 4: The final design for a single thermal isolation joint unit, exploded (above) and assembled (below). Spring washers between the sapphire discs and outer copper components are not shown.

A value of 2.57 μW was measured for an upper temperature of 1.1 K, in agreement with the specifications. For comparison, we show the conductance of a hypothetical support using three rods of Vespel® SP-22, which is one of the best known thermal insulators at these temperatures [36, 37]. The diameter of each rod is arbitrarily taken to be 10 mm (the same as the sapphire discs), and the length is approximately 80 mm, chosen to give the same conductance as the sapphire prototype support at a temperature of 1 K. Since the sapphire joints are much smaller, this clearly demonstrates the ability of sapphire joints to provide compact and rigid isolation supports, although it can be seen that Vespel becomes more attractive as the upper temperature of the structure is increased above 1 K.

Tests at room temperature showed that the mechanical requirements of the prototype were met. The inner (“cold”) section was loaded axially, and the deflection measured with dial gauges. Repeated loading of the support up to 10 kg showed no hysteresis in the measured deflection, with a load of 5 kg producing a repeatable deflection of 8 μm. Measurements over a 65 hour period with a 5 kg load showed no further movement or creep; the smallest amount which could have been measured was approximately 0.5 μm.

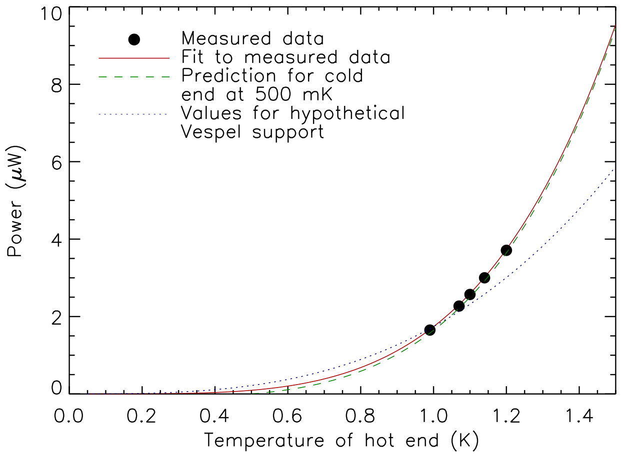

Figure 5: Measured values for the power transferred through the prototype support structure. Also shown are predicted values for different hot end temperatures, at cold end temperatures of both 80 mK (as used for the measurements) and 500 mK. The calculated power is also shown for a hypothetical Vespel® SP-22 structure as described in the text. The conductivity of Vespel® SP-22 is taken from Refs. [36] and [37].

For the final design, the copper surfaces were replaced with aluminium for compatibility with the overall instrument design. Measurement on one of these joints at millikelvin temperatures produced similar results to the equivalent joints using copper. This was expected since we believe that the dominant resistance is at the sapphire-powder-sapphire interface. Eight further joints were constructed to the same design. Similar conductance values were measured at 4 K, though with considerable variation (± 20% from the mean value). Since this is much larger than the calculated error in the measurement, we assume that the variation is intrinsic to the samples, and would therefore consider it prudent to measure all such joints before using them in support structures. Eight joints were used in the construction of two full supports. These have now been in use in the SCUBA-2 instrument for over a year, and have undergone seven cool-downs with no noticeable change in performance.

3. DEMOUNTABLE THERMAL CONTACT

A. Samples

Two demountable thermal contact samples were measured. Sample A, shown in Fig 6, used thermal contraction on cooling to provide the clamping force between two copper surfaces. This was achieved by using a central core of Invar®, a material which has a very low thermal contraction. The metal surfaces therefore contract around this core as they are cooled, and are forced together. The sample consisted of three parts. One part was made by permanently pressing the Invar core into a copper jacket to form a cylinder. The joint was then made by fitting the cylinder into recesses in the two remaining parts. The components were machined to a tight slide fit, so that at room temperature the joint could be easily taken apart. A small screw was used to hold it together at room temperature. It should be noted that the sample has two thermal interfaces in series. The contact area for *each* interface was 745 mm^2. This joint has the advantage that it provides accurate mechanical positioning of the two sides relative to each other, and does not require access to be available in order to tighten bolts. It does, however, require very accurate machining.

Sample B was a conventional joint between copper and BeCu, consisting of two flat surfaces bolted together by four M4 aluminium screws, tightened to a torque of 175 N cm. Aluminium contracts more than both copper and BeCu on cooling, ensuring that the clamping force is maintained. This design is much simpler to construct than that of sample A. The contacting surfaces were circular, with a diameter of 55 mm.

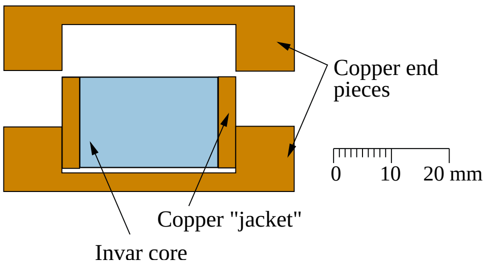

Figure 6: Scale cross-section of the demountable thermal contact sample A, with the upper end-piece not in place.

The copper components were made using regular commercial (electrolytic tough pitch) copper. The beryllium copper was the high conductivity beryllium copper alloy C17510 with temper TF00. No underlayer was used when gold plating. The thickness of the gold plating was not measured, but is believed to be approximately 2 μm.

B. Measurements

Our measurements were made in a paramagnetic salt adiabatic demagnetisation refrigerator and a dilution refrigerator, enabling temperatures below 100 mK to be reached. Exchange gas was not used to cool the apparatus in either cryostat.

The conductance was measured using the “two heater” method, in which a heater is mounted on each side of the joint. A thermometer is mounted on one side only (the “hot” side), and the other is heat sunk to the millikelvin stage of the cryostat (the “cold” side).

In this method, to measure conductance at a particular temperature, power is first applied to the heater on the cold side, and the equilibrium thermometer temperature measured. Since no power is applied to the hot end heater, there is essentially no thermal power flowing from the hot side to the cold side, and the sample can thus be assumed to be in thermal equilibrium. The measurement therefore establishes the temperature of the cold side of the joint with a known applied power; in general this will be higher than the heat sink temperature due to a finite thermal impedance across the interface between the sample and heat sink.

The same amount of power is then applied instead to the hot side heater, and the temperature measured again. The thermometer now gives the temperature of the hot side of the sample, and since the power is the same as before, the cold end temperature will remain the same and is thus known.

The thermal conductance can then be determined from the applied power and the measured temperature difference across the joint. For more accurate results, measurements are taken with a series of different powers applied to the hot side heater. The power to the cold side heater is then adjusted so that the total power, and thus the temperature of the cold side, remains constant.

This method has the advantage that only one calibrated thermometer is needed for each sample. In addition, since only one thermometer is used, errors caused by different thermometers having different calibrations are avoided. This is particularly important when measuring highly conducting samples, since temperature differences will be small.

The heaters were metal film resistors. An NTD germanium thermometer was used to measure temperature. These thermometers have the advantage of a simple analytical calibration function [38]. This is valuable when measuring temperature differences which are less than the spacing in calibration points, since the interpolation between points is based on the expected form, rather than the behaviour of an empirical fit. Additional measurements were made using a ruthenium oxide (RuO) thermometer. We estimate the accuracy of a conductance measurement at a given temperature to be better than ± 20%.

Sample A was first measured with bare copper surfaces. The surfaces were then gold plated, and the sample measured again on two further cool-downs. Good agreement was seen between these two cool-downs, and between measurements made using two different thermometers with entirely different calibrations. Sample B was only measured with the surfaces gold plated.

The measurements were made at temperatures below 1 K. It is more common to make such measurements at higher temperatures. However, extrapolating to lower temperatures only yields upper limits on conductance, since the temperature variation may be linear or show a stronger temperature variation. Conversely, measurements made below 1 K give good lower limits for the conductance at higher temperatures, which is more likely to be useful.

Another advantage of our measurements is that the thermal conductance was measured directly. Most quoted results for joints intended as thermal contacts are actually measurements of the electrical resistance of the joints, since this is a much easier measurement to make. While resistance measurements can be converted to a value for the thermal conductance via the Wiedemann-Franz law [39, 40], this adds a source of uncertainty.

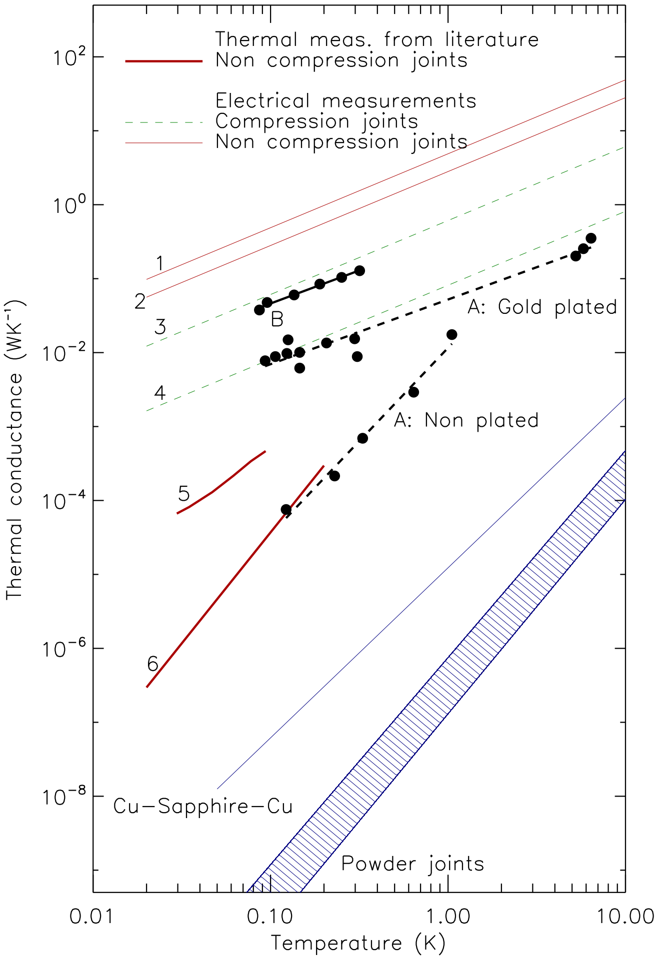

Figure 7: Measured conductance of the demountable thermal contacts A and B (●) as labelled; results for sample A are shown before and after gold plating. The lines passing through the points show least-squares fits to the data. For comparison, various results from the literature for demountable contacts are shown, as follows (all joints are between gold plated copper surfaces unless otherwise mentioned): (1) bolted joint between platinum and silver [7]; (2) bolted joint [8]; (3) and (4) nylon sleeve compression joints (Refs. [9] and [10] respectively); (5) non gold plated bolted joint [11]; (6) bolted joint with indium layer [12]. Direct thermal conductance measurements (curves 5 and 6) are shown as thick lines, and values predicted from electrical measurements and the Wiedemann-Franz law (curves 1-4) as thin lines. The conductance of some of the sapphire thermal isolation joint measurements, taken from Fig. 3, are also shown.

C. Results and discussion

The measured conductance values are shown in Fig. 7, along with other measurements from the literature. For sample A, the conductance before gold plating was relatively poor, and the temperature dependence was much sharper than linear. This suggests that — as would be expected — the conduction is primarily through the oxide layers that inevitably form on the copper. Since copper oxide is a dielectric, this prevents good metallic contact. The values are consistent with those measured for a copper joint with an intermediate indium layer [12] (curve 6 in Fig. 7); at these temperatures indium superconducts and thus acts like a dielectric. A joint with somewhat higher conductance [11] (curve 5) also has a less steep temperature dependence, suggesting more electronic conductance.

After gold plating, the conductance was greatly improved, and the temperature dependence was close to linear. This agrees with the general consensus that good metallic contact is obtained between clean gold plated surfaces, and that the conductance will then vary linearly with temperature. These measurements highlight the importance of removing the oxide layer for joints used at millikelvin temperatures; the difference in conductance is over two orders of magnitude at 100 mK, and will be even larger at lower temperatures.

Two groups have made measurements on compression joints in which the clamping force was provided by an outer nylon sleeve [9, 10]. Curves 3 and 4 in Fig. 7 show the best result from each group. The results differ by approximately one order of magnitude; our joint is comparable to the lower of the two values. The nylon joints had somewhat larger contact areas than sample A (2370 mm^2 and 1824 mm^2 for curves 3 and 4 respectively); unlike sample A, they consisted of a single interface each. It would be possible to re-design sample A so that it was made of two pieces, and thus contained only one thermal interface. Increasing the length of the cylinder from 8 mm to 40 mm would also be practical. These changes should increase the conductance by a factor of 10, resulting in a similar value to the best nylon joint. The advantage of this joint design over those using nylon is that it is more robust, and the performance is less likely to alter after repeated thermal cycling since it consists entirely of metal components.

A linear temperature dependence was also seen for sample B (Fig. 7). The highest measured value we are aware of for a bolted joint [7] (curve 1) is approximately an order of magnitude higher than for sample B. These measurements were made on a joint between silver and platinum. The highest value for a copper-copper joint [8] (curve 2) is slightly lower. We calculate a contact pressure of approximately 9 kN for sample B, based on the torque applied to the screws [22]. We estimate similar pressures, of 10 kN and 6 kN respectively, for the measurements shown in curves 1 and 2. The conductance of sample B could presumably be increased by either using a higher torque, or increasing the number of screws. However, extrapolating to a temperature of 50 mK gives a conductance of approximately 20 mWK^{-1}, well above the specification of 2 mWK^{-1}. Improvement is therefore not necessary.

A potential problem is that joints made with different materials can degrade with time due to differential motion on thermal contraction. However, since BeCu has a similar thermal expansion coefficient to copper, this should not be a problem for this joint.

It is clear that the use of a material which is hard to deform on one side of the joint does not prevent good conduction; this was also the case with the results shown for a platinum-silver joint (curve 1). It is true that the contact area for sample B is somewhat larger than for most bolted joints that have been measured; however, this should not be important since the conductance depends mostly on the contact force and not the area.

It should be noted that the samples corresponding to curves 1 to 4 were actually measured electrically at 4.2 K, with the millikelvin thermal conductance predicted from the electrical resistance by the Wiedemann-Franz law. This is valid for bulk copper and does appear to be valid for contacts [41], although direct evidence is somewhat limited [13].

4. CONCLUSIONS

We have developed compact thermal isolation joints utilising the low thermal conduction between two sapphire surfaces separated by alumina powder. We believe that the low conductance of these joints is due to a very small true contact area. An important observation is that the conductance through the joints is not proportional to area, and thus quoting results as conductance per unit area is not appropriate. The variation of conductance between nominally identical samples was significant compared with the calculated experimental error, with values which varied by ± 20% from the mean value for nine such samples (this should be compared with an experimental error of less than 3 %). The best joint design was used to construct a rigid mechanical support capable of supporting a mass of over 10 kg with a low thermal conduction; a heat leak of 2.57 μW from 1.1 K to 80 mK was measured. Two supports of this design have been in use in the SCUBA-2 instrument for over a year. Despite multiple cool-downs they have shown no noticeable change in performance.

We have also carried out thermal conductance measurements on two demountable thermal contacts. A copper joint using differential thermal contraction to provide the clamping force had a performance an order of magnitude less than the best compression joint values from the literature. However, a simple re-design should improve the conductance by a factor of 10. A bolted joint between copper and beryllium copper had a conductance of 46 mWK^{-1} at 100 mK, increasing linearly with temperature. We are not aware of any higher directly measured values on purely mechanical contacts in this temperature range; the best value predicted from 4.2 K electrical measurements using the Wiedemann-Franz law is approximately an order of magnitude higher.

The difference of over nine orders of magnitude between the measured conductance at 50 mK of the best thermal insulator and the best thermal conductor highlights the importance of understanding thermal contact in cryogenic systems.

Both sets of measurements were carried out as part of the development programme for the SCUBA-2 astronomical instrument [1, 2]; in both cases the design requirements were achieved.

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