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COMMENT

Comment on 'thermal boundary resistance of mechanical contacts between solids at sub-ambient temperatures'

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Abstract
A paper by Gmelin *et al* examines the thermal contact resistance between copper surfaces above 1 K. It was concluded that dielectric and metallic interposers significantly increase the conductance of demountable joints. I argue that an extrapolation of electrical resistance measurements, and of thermal measurements at lower temperatures, implies that it is possible to construct considerably better joints without interposers. Moreover, dielectric interposers would *reduce* the conductance of such joints.

A paper by Gmelin *et al* [1] in this journal examines, among other things, the thermal contact resistance between copper surfaces above 1 K. A conclusion drawn is that for demountable joints the smallest contact resistance is obtained—other things being equal—if a thin interposing material such as Apiezon N grease or indium is used. This conclusion is supported by new measurements along with a compilation of data from the literature. The literature data is restricted to thermal measurements at temperatures above 1 K.

The mechanism for this improvement is thought to be an increase in the contact area when an interposer is used. When two surfaces are placed in contact, they only actually touch at a small number of points. A softer material pressed between two surfaces will deform and increase the number of contact points.

However, an alternative school of thought is that extremely good thermal contact can be made between metals if the surfaces are pressed firmly together with no interposing material. Indeed, it is claimed that for such a 'dry' joint the resistance can be almost as small as a bulk, continuous part [2]. Support for this point of view comes from many measurements showing extremely low contact resistances in such a configuration, with the pressure between the surfaces obtained either by screws, or a nylon ring which contracts during cooling. The relevant papers are largely concerned with the design of experiments to be conducted well below 1 K, and describe two types of measurement. Either thermal conduction data was taken below 1 K, or the electrical resistance was measured at 4.2 K. Consequently, although some of these papers were referred to in [1], the results were not shown in the compilation of data. Electrical measurements dominate, due to their simplicity compared with thermal measurements.

While a direct comparison is not possible, both types of result can be compared with the data in [1] by making some reasonable assumptions. Thermal conductance data can be extrapolated to above 1 K by assuming a linear dependence on temperature. This would be expected for electronic conduction, while if the conduction is through a dielectric (such as an oxide layer), a higher power would be expected. Assuming a linear dependence should therefore give a lower limit for conductance.

Electrical resistance data can be converted to an equivalent thermal conductance using the Wiedemann–Franz law [2]. As described in [1], this has been shown to be valid for the electronic component of thermal contact conductance. Any additional phonon heat transport will have the effect of increasing the total thermal conductance over the predicted value. Therefore, again the value obtained might be expected to be a lower limit. However, it should be

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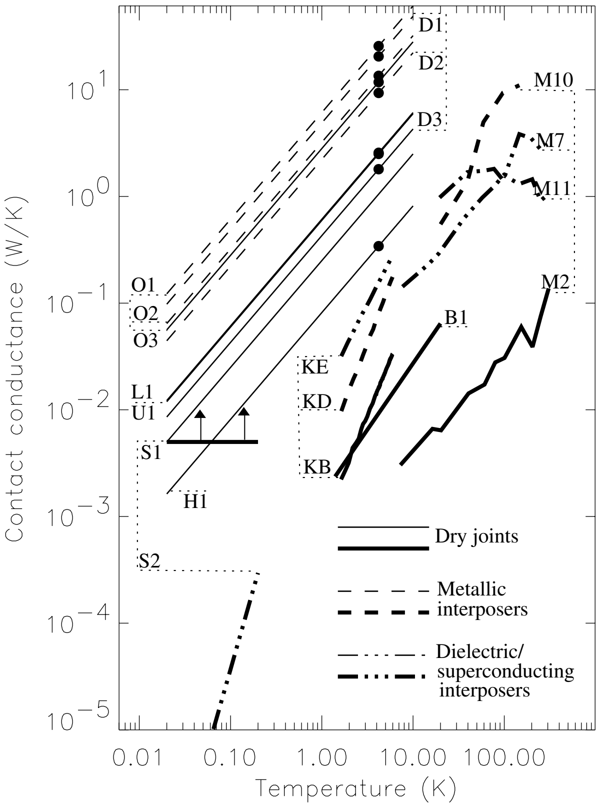

Figure 1. Comparison of experimental data. Conductance measurements are shown as thick lines. Extrapolations to higher temperatures are shown as thin lines. Values calculated using the Wiedemann–Franz law are shown as full circles at the temperature of measurement, and extrapolations to other temperatures as thin lines. The datasets are as follows (codes used in [1] are shown in parentheses). *Group A*: M2, Cu/Cu; M7, Cu/Apiezon N/Cu; M10, Cu/In/Cu; M11, Cu/Cryocon/Cu [1]. KB, Cu/Cu; KD (41c), Cu/In/Cu; KE (41b), Cu/Apiezon N/Cu [6]. B1 (36a), Cu/Cu [7]. *Group B*: D1, Cu/In/Cu; D2, Cu/Ag adhesive/Cu; D3, Cu/Cu [8]. O1, Cu/In/Cu; O2, Cu/Ag paste/Cu; O3, Cu/Cu [9]. L1, Cu/Cu [5]. U1, Cu/Cu [10]. H1, Cu/Cu [11]. S1, Cu/Cu; S2, Cu/In/Cu [12]. Note that S1 is a lower limit; the lowest temperature value is extrapolated to higher temperatures. Lines L1 and U1 overlay each other.

pointed out that deviations from the Weidemann–Franz law have been occasionally found in bulk materials [3], and also for contacts between heavily deformed copper surfaces [4]. There is, therefore, a possibility that a given predicted thermal conductance is too high by as much as an order of magnitude.

The results are shown in figure 1. Contact conductance is plotted, rather than conductance per unit area. This is justified by the common observation that the heat transfer is approximately independent of the nominal contact area. The figure is limited to data from purely mechanical contacts. For each paper, the best results are shown from each configuration measured. Most authors agree that the best conduction occurs when the surfaces are clean and flat, and pressed together with the highest possible force. Gold plating is generally seen to improve the conductance, although cleaning the surfaces immediately prior to making contact instead has been shown to give similar results [5].

It can easily be seen that the results fall into two categories. Those plotted in [1], described below as group A, show large increases in conductance when interposers (metallic or dielectric) are used. For the remaining data (group B), metallic interposers give an increase in conductance. An indium interposer caused a very large *decrease* in conductance below 200 mK[2]. It should be noted here that a metal sufficiently far below the superconducting transition temperature acts thermally as if it were an electrical insulator [2]. Indium has a transition temperature of 3.4 K, and therefore for these measurements would be expected to act similarly to a dielectric. This data (set S2 in figure 1) seems to be consistent with the dielectric interposer measurements at higher temperatures (KE, M7, M11).

An obvious conclusion is that using the extrapolations described above, the dry joint conductances in group B are much larger than all the measurements in group A, both for dry joints and with interposers. In fact, they have conductances comparable to the best of the glued and soldered joints described in [1]. Even if the true thermal conductance is an order of magnitude lower than the prediction from electrical resistance, the joints still show clear superiority over those in group A. A possible mechanism for this is as follows.

For the poorer joints (group A), conduction is predominantly via phonons. This is suggested by the fact that the temperature dependence of conductance for these joints generally follows a power law with a coefficient greater than one. In addition, for set B1, electrical resistance measurements showed that only a small fraction of the heat transfer could be electronic. Using a dielectric interposer then increases the actual contact area, while the lost electronic contribution to the conductance is small. Oxide layers, frozen gases, or other surface contamination may be responsible for the lack of electronic conduction in these joints [12].

However, for the better joints (group B), good electronic conduction is obtained. This conclusion is supported by measurements of a linear temperature dependence of thermal conductance over limited temperature ranges [4, 12]. In this case, any increase in contact area due to a dielectric (or superconducting) interposer would be at the expense of electronic contact. This is particularly significant below 1 K, where the difference between phonon and electronic conduction becomes very large. Another problem is the boundary resistance due to acoustic mismatch of phonons (sometimes referred to as Kapitza resistance) [2]. This also becomes very large below 1 K, and, unlike the bulk thermal resistance, is not minimized by making an interposer as thin as possible. (This could also be a problem even for the joints in group A at very low temperatures.) Another possible problem at temperatures well below 1 K is the decoupling of electrons and phonons in the bulk material, reducing the phonon conductance across the contact further [13].

Since for the very best joints metallic interposers cause only a relatively small increase in conductance, it seems very unlikely that dielectric interposers would be of use even above 1 K.

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[2] Measurements have also been made where an indium interposer did *not* drastically decrease the conductivity below 1 K [12]. In this case it is believed that the copper surfaces were touching through the indium. It should also be noted that a magnetic field, applied either deliberately or inadvertently, can destroy superconductivity.

In conclusion, the available data suggest that the conduction through relatively poor copper–copper contacts is helped by interposers, which may be dielectric or otherwise. However, it is possible to design joints with no interposer which have much better conductance. For these joints, an improvement can be made by using an interposer which allows electronic thermal conduction, but dielectric (or superconducting) interposers should not be used. Below 1 K, where boundary resistance becomes significant, interposers may not be the best option even for the poor joints. However, more measurements are required to confirm these conclusions, since they rely on the extrapolation of existing data.

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