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Heat Flow at Pressed Contacts

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Abstract

Observations have been made of the temperature changes that occur when a heated copper probe is pressed against hard samples of different thermal conductivity under a range of mechanical loads. A comparison is made between the electrical and thermal resistance when the test sample is an electrical conductor. The effect of replacing the ambient air by helium is also studied. The results are analysed in terms of a theoretical model that has been proposed for a recently developed thermal comparator, but they should also be relevant to pressed contacts in general. The most significant observation is that of a very weak dependence of the thermal contact resistance on load.

Introduction

An understanding of the flow of heat at the contact between two solids is important in several fields. For example, the studies by Jacobs and Starr (1939) and Berman (1956) are relevant to thermal switches at cryogenic temperatures. An excellent review of experimental and theoretical work in this field has been presented by Fried (1969). The studies by Powell and his coworkers (Clark and Powell 1962; Powell 1969) on so-called thermal comparators have given an extensive range of data that are relevant to the problem of heat transfer at contacts.

Powell's earlier measurements, which were subjected to a detailed theoretical analysis, involved transient temperature measurements but they led to the introduction of a direct-reading steady-state comparator. An essential feature of the direct-reading instrument is the determination of the temperature at the point of contact. More recently, a new type of thermal comparator, in which the temperature is measured close to but not at the contact, has been described (Goldsmid and Goldsmid 1979; Goldsmid 1979). In this version, the probe is formed from a copper–constantan thermocouple, one junction being heated while a copper tip near the other junction is placed against the test material. The flow of heat through the copper branch of the couple and across the interface gives rise to a temperature difference and, hence, to a thermal e. m. f., the magnitude of which is related to the thermal conductivity of the sample. The comparator is suitable for use with materials that are at least as hard as the copper tip; it incorporates a spring that undergoes a fixed compression, thus ensuring that the area of contact is more or less constant.

For materials of very high thermal conductivity (such as diamond), nearly all the heat flowing through the copper branch of the couple also passes into the sample through the interface. However, for poorer conductors the flow of heat around the interface is also important. It was found from experiments on a number of materials that the behaviour can be described using a simple theoretical model involving five thermal resistors, the values of which are determined somewhat empirically. It is the purpose of the present work to investigate the parameters of the theoretical model in more detail. To this end, an experimental probe has been built, in which the load on the contact can be varied and the ambient gas can be other than air. It has also been possible to determine the electrical resistance at the interface between the probe and an electrically conducting sample.

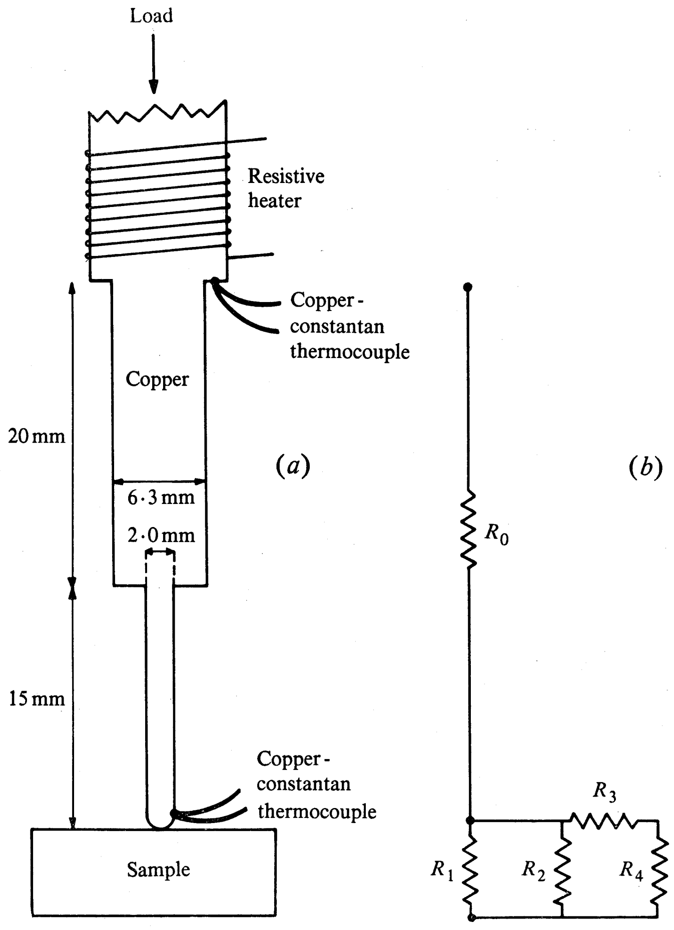

Fig. 1. Experimental thermal probe showing (*a*) the details of the apparatus and (*b*) the theoretical network of thermal resistors used to describe its behaviour.

Most of the previous investigators have been concerned with contacts between pairs of metals, whereas in our work one of the materials was invariably a hard non-metal. Similar materials were included among those studied by Powell (1969) but his loadings were much smaller than those employed here.

Experimental Procedure

The probe used in these experiments is illustrated in Fig. 1*a*. It consists of a copper cylinder of 15 mm length and 2 mm diameter, with a hemispherical tip, that forms an extension of another cylinder of 20 mm length and 6·3 mm diameter, above which is attached an electrical heater of 28·5 Ω resistance. Copper–constantan thermocouples, made from wires of 0·11 mm diameter, are soldered to the probe just above the tip and just below the heater. The probe is mounted on the movement of a Zwick indenter, in place of the indenting tool, so that it can be brought down slowly against a horizontal surface with a specific loading. Not shown in the diagram are the glass insulation that surrounds the probe to within almost 1 mm of the tip and the flexible enclosure that allows the ambient air to be replaced by some other gas. Fig. 1*b* shows the resistance network model that was used to describe the behaviour of the thermal comparator (Goldsmid 1979) and which is now applied to the probe employed in this work. Here R_0 is the thermal resistance of the probe, R_1 that of the interface with the sample and R_2 the resistance corresponding to heat flow through the surrounding gas. Further, R_3 and R_4 represent the thermal resistance of the regions immediately surrounding the actual interface, R_3 being constant for a given gas and R_4 depending on the thermal conductivity of the test sample.

In the performance of tests, a steady current is passed through the heater so that it reaches a temperature of 95 K above the surroundings. Prior to each measurement the temperatures of the two ends of the probe become steady. The probe is then lowered until it presses against the sample with a pre-selected load in the range 0–50 N. The temperature difference between the thermocouples is found to rise rapidly after the load is applied, reaching a maximum value in about 10 s and then falling extremely slowly. We have found that the temperature at the upper end of the probe changes by a negligible amount during this 10 s period and it appears as if the maximum temperature difference lies very close to the steady state value that would exist if the heated end of the probe were maintained at a fixed temperature for an indefinite period.

We have taken readings, for successively increasing and then decreasing values of the load, on flat smooth surfaces of samples of silicon, germanium, $Si_{85}Ge_{15}$ and glass, all of about 5 mm thickness. For germanium, measurements were also made, over a range of loadings, of the electrical resistance between the probe and the sample, this resistance being dominated entirely by the interface; the electrical resistivity of the germanium was determined separately using a four-probe apparatus. Both electrical and thermal measurements were carried out with the bulk of the samples at room temperature (25°C).

After the experiments in air had been completed, a similar set of thermal measurements was performed using helium gas in the enclosure. The current through the heater was increased so that the temperature at the upper end of the probe retained the same value as in air, that is, 95 K above ambient.

Experimental Results

Fig. 2*a* shows the maximum e.m.f. V between the two thermocouple junctions plotted against the load W for the four test materials in air. Before contact was made there was an e.m.f. of 0·22 mV arising from heat losses to the surroundings. For any particular load we found that the results could still be fitted (with a redundancy of data) by the equation given previously for the thermal comparator,

$$\frac{V}{V_0 - V} = \frac{R_0}{R_2} + \frac{A}{1/\lambda_0 + 1/\lambda} + \frac{1}{B + C/\lambda}, \tag{1}$$

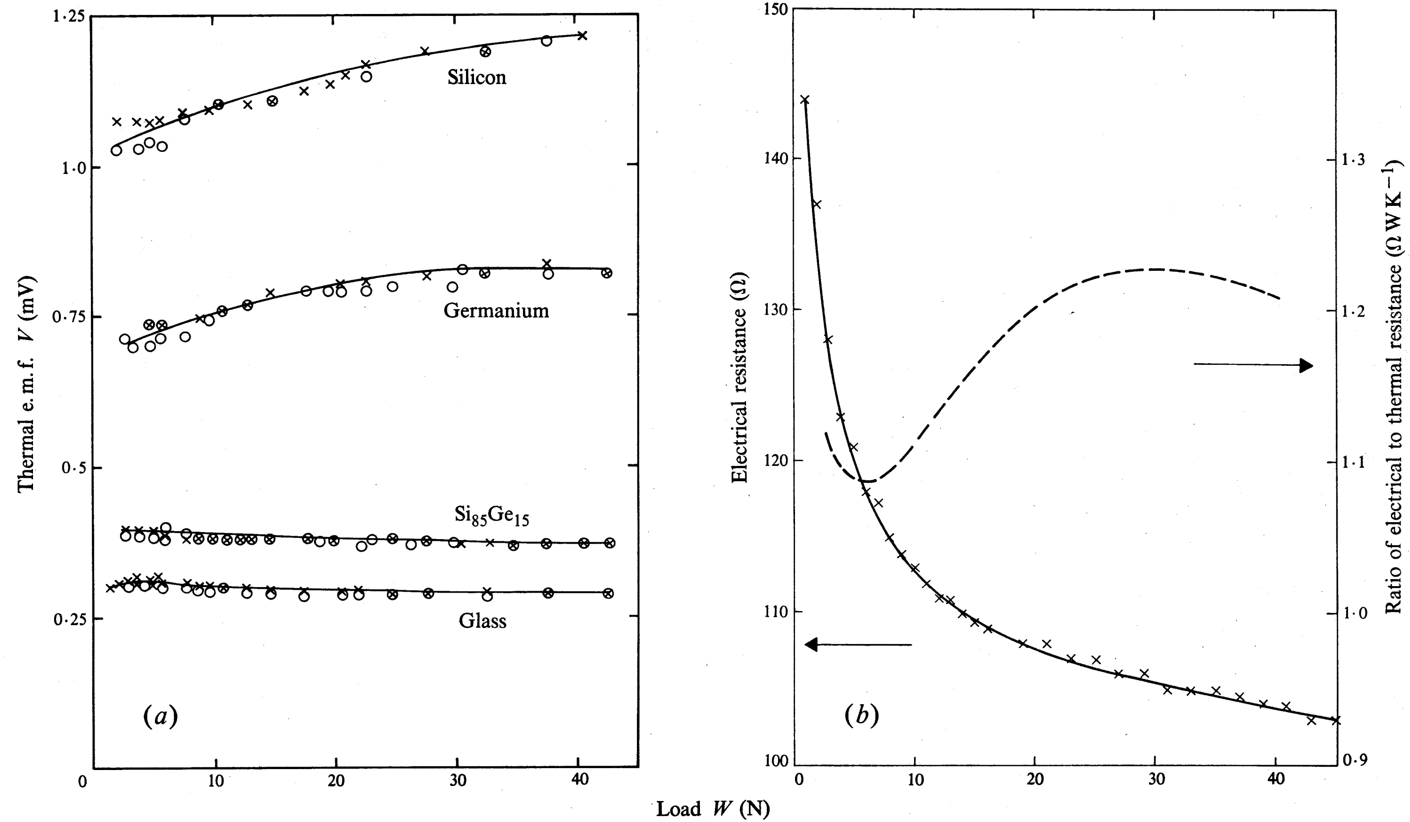

Fig. 2. Plots of (*a*) the thermal e. m. f. V against the load W for different test materials in air and (*b*) the electrical resistance (solid curve) and the ratio of electrical to thermal resistance (dashed curve) against W for the interface between the copper probe and a germanium sample.

where V_0 is the e. m. f. corresponding to the output of the upper thermocouple with its reference junction at the ambient temperature, λ_0 is the thermal conductivity of copper and λ that of the test material. The constants A, B and C are such that $A = 4r_1 R_0$, where r_1 is the effective radius of the interface (it would be the actual radius if the contact were circular), $B = R_3/R_0$ and $C = \lambda R_4/R_0$. The origins of equation (1) have been discussed previously (Goldsmid 1979).

Table 1. Enhancement of thermal e. m. f. V with helium as the ambient gas for materials of different thermal conductivity

Material	λ ($W m^{-1} K^{-1}$)	Increase of V (mV)	Increase of $V/(V_0 - V)$
Silicon	145	0·04	0·017
Germanium	64	0·05	0·018
$Si_{85}Ge_{15}$	5·8	0·14	0·042
Glass	0·7	0·18	0·051
None		0·18[A]	0·049

[A] Increase in e. m. f. before contact made.

A particularly noticeable feature of the results shown in Fig. 2*a* is that the thermal e. m. f. varies very little with the load. This is especially so for the poorer conductors $Si_{85}Ge_{15}$ and glass and, in fact, for these materials there is a marginal decrease in V as the load rises. We found that the electrical resistance at the interface between the probe and the germanium sample also varied slowly with load as shown in Fig. 2*b*.

When the thermal measurements were repeated using helium as the ambient gas the thermal e. m. f. V and, more particularly, the ratio $V/(V_0 - V)$ were increased. This enhancement of $V/(V_0 - V)$ was substantially independent of load and greatest for the poorer conductors as shown in Table 1.

Discussion

The features of the experimental results that we should attempt to explain are:

(1) the general nonlinear dependence of the thermal e. m. f. on the thermal conductivity of the test material for a given load;

(2) the rather weak dependence of the thermal e. m. f. on load for the better thermal conductors and its almost negligible dependence on load for the poorer conductors;

(3) the relative variations with load of the thermal and electrical contact resistances for the germanium sample;

(4) the greater effect of the replacement of the ambient air by helium for poor conductors than for good conductors.

As has been stated already, the nonlinear dependence of e. m. f. on λ for a given load can be described by equation (1). The following parameters are those which give a good fit at the load of 10 N:

R_0/R_2	A ($m K W^{-1}$)	B	C ($W m^{-1} K^{-1}$)
0·055	$2 \cdot 3 \times 10^{-3}$	25	19

The fit for silicon and germanium is quite sensitive to the parameter A and establishes its value to about $\pm 5\%$. Likewise, the predicted behaviour for $Si_{85}Ge_{15}$ and glass is sensitive to the choice of B and C so that these parameters are established to about $\pm 20\%$.

In order to find absolute rather than relative values for the thermal resistors R_1, R_2, R_3 and R_4 in Fig. 1*b* it is necessary to know the thermal resistance R_0 of the probe between the two thermocouples. Assuming the thermal conductivity of copper to be $400\ \mathrm{W\,m^{-1}\,K^{-1}}$, we obtain $R_0 = 13{\cdot}5\ \mathrm{K\,W^{-1}}$. Using this value of R_0 we have calculated the thermal resistance of the germanium–copper solid–solid interface as a function of load, assuming that B and C are load independent. This assumption is not critical since the term involving B and C in equation (1) accounts for less than 20% of the total thermal conductance. The interface resistance R_1 is found to have values ranging from about $116\ \mathrm{K\,W^{-1}}$ for a load of $2{\cdot}5$ N to about $85\ \mathrm{K\,W^{-1}}$ for a load of 40 N. The dashed curve in Fig. 2*b* shows the ratio of electrical to thermal resistance plotted against load for the germanium sample and it may be seen that this ratio lies between $\sim 1{\cdot}1$–$1{\cdot}2\ \Omega\,\mathrm{W\,K^{-1}}$ over the whole range.

Four-probe measurements at room temperature showed the electrical conductivity σ of the germanium to be $40{\cdot}9\ \Omega^{-1}\,\mathrm{m^{-1}}$, while the thermal conductivity λ is $64\ \mathrm{W\,m^{-1}\,K^{-1}}$. The ratio λ/σ, which should be equal to the ratio of the electrical to the thermal resistance at the interface when this is dominated by the poorer conductor, germanium, is then $1{\cdot}56\ \Omega\,\mathrm{W\,K^{-1}}$ (this is, of course, much greater than the ratio to be expected for a metal since the thermal conductivity of germanium is dominated by the lattice component). This ratio is fairly close to that shown by the dashed curve in Fig. 2*b* and the agreement would be much better if the variation of the thermal conductivity of germanium with temperature was taken into account; the mean temperature of the sample in the thermal measurements is, of course, substantially greater than 25°C and lattice conductivity falls as the temperature rises.

At a load of 10 N, the value of A indicates that the effective radius of contact r_1 is 44 μm. It is remarkable how little this radius increases with load. Thus, using the data of Fig. 2*a*, we find an increase in r_1 to no more than 52 μm as the load W is increased to 40 N. Over this range it is a good approximation to set $r_1 \propto W^x$, where $x = 0{\cdot}12$. It is uncertain whether we should apply elastic or plastic flow theory to our system but, in fact, neither can explain the observed value of x if one assumes a simple circular contact. If one used elastic theory for isotropic media (as an approximation), the radius of contact would be (Bowden and Tabor 1950)

$$r_1 \approx 1{\cdot}1\{\tfrac{1}{2}Wr(E_0^{-1}+E^{-1})\}^{\frac{1}{3}}, \tag{2}$$

where r is the radius of the hemispherical tip, E_0 is Young's modulus of copper and E that of the test material (which does not change much from one material to another). The relation (2) suggests that x should be equal to $\frac{1}{3}$. If the copper tip yields under the load, the area of contact should become proportional to W and x should be equal to $\frac{1}{2}$.

We explain the low measured value of the index x as follows. The interface obviously consists not of a single circle of contact of small area but of a large number of isolated contacts spread over a larger area. This makes the effective radius of contact, as determined from the electrical or thermal resistance, much larger than it would otherwise be. The effect of increasing the load is apparently to increase the number of the isolated contacts without increasing the size of the region in which such contacts are to be found. This mechanism has been discussed by Fried (1969) but there does not seem to be a satisfactory mathematical description of it.

The value of x determined from the thermal measurements on silicon is about the same for germanium. For $Si_{85}Ge_{15}$ and glass, however, the solid–solid interface accounts for only about 10% and 2% of the total thermal conductance respectively and, as actually observed, the thermal e. m. f. is almost independent of the load, though the slight fall with load of the e. m. f. is unexpected.

Turning now to the observations in helium, we suppose that the value of $V/(V_0 - V)$ is affected only through the terms $1/(B + C/\lambda)$ and R_0/R_2 in equation (1). Thus it is not surprising that the change in $V/(V_0 - V)$ was observed to be independent of the load. The thermal e. m. f. prior to making contact has about twice the value in helium that it has in air. The thermal conductivity of helium is about six times that of air (this and other heat conduction data were obtained from Weast 1976–77), but it can be assumed that heat is lost from the probe tip by convection and radiation as well as conduction. The last column of Table 1 shows that the effect of helium on $V/(V_0 - V)$ is significantly less for the good conductors (silicon and germanium) than it is for the poor conductors ($Si_{85}Ge_{15}$ and glass) and this is totally unexpected from equation (1). Surely the additional conductance associated with the increase of R_0/R_2 would be the same in all cases and the expected change in the parameter B would only lead to an increase in $V/(V_0 - V)$ for samples of higher thermal conductivity.

The results obtained in helium, therefore, show that our model is somewhat inadequate. It is probable that the fault lies in the assumption that the three parallel heat paths through R_1, R_2 and $R_3 + R_4$ are independent of one another. In fact, one would expect that the enhancement of the conduction of heat through one branch would increase the resistance of one of the other branches whenever the flow paths overlapped one another. However, it has so far not been found possible to put the hypothesis in a quantitative form.

Conclusions

The most interesting result of these experiments is the observation of the very weak dependence of the thermal resistance of the interface on the load. This result, which is consistent with the measurements on electrical resistance for germanium, can be explained in terms of a multiple-point contact within a more or less fixed perimeter. Our model is consistent with a very weak dependence of the total thermal resistance on load for poor thermal conductors, although the very slight decrease in thermal e. m. f. with increasing load that was noticed for $Si_{85}Ge_{15}$ and glass has not been explained. Only a qualitative hypothesis to account for the effect of replacing the ambient air with helium samples of different thermal conductivity has been put forward, but the load independence of increase of thermal e. m. f. in helium is as expected.

Our apparatus was unsuitable for studies with small loads and could not be used with a vacuum environment for the probe and sample. A more detailed analysis of our results is probably not worth while until further work has been done with equipment in which these deficiencies are made good.

Acknowledgment

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