Effect Of The Thickness Of A Thermal Interface Material (Solder) On Heat Transfer Between Copper Surfaces

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Abstract

Solder applied in the molten state was used as a thermal interface material between copper surfaces. The effect of the solder thickness on the heat transfer between the copper surfaces was studied by measuring the thermal contact conductance using the laser flash method. Increasing the thickness of solder from 10 to 30 mm was found to increase the heat transfer time (temperature rise time) by 25%. The effect is akin to replacing solder with an interface material that is 80% lower in thermal conductivity. It is also akin to decreasing the thermal contact conductance of the solder-copper interface by 70%. Thus, minimization of the solder thickness is recommended in practice.

Key words

Thermal Interface, Thermal Contact, Solder, Copper, Heat Transfer, Conductance, Laser flash

1. Introduction

Thermal contacts are commonly encountered in the industry and in homes. A thermal contact can be between a hot (or cold) plate and an object to be heated (or cooled), and between two hot objects (or two cold objects) in an assembly. An example is the thermal contact between a printed circuit board and a heat sink in an electronic package. Heat dissipation, is a critical problem that limits the reliability, performance and further miniaturization of microelectronics. The thermal resistance at a contact results in a thermal barrier, which leads to inefficient heating or cooling, and hence the wasting of energy. To decrease the thermal resistance at the contact, a thermal interface material can be placed at the interface between the two objects.

Solder is commonly used as a thermal interface material for enhancing the thermal contact between two surfaces. This is because solder can melt at rather low temperatures and the molten solder can flow and spread itself thinly on the adjoining surfaces, thus resulting in high thermal contact conductance at the interface between solder and each of the adjoining surfaces. Furthermore, solder in the metallic solid state is a good thermal conductor. Although solder is commonly used and the solder thickness can vary greatly in practice, the effect of its thickness on the heat transfer has not been previously addressed. On the other hand, the effect of solder thickness on the electrical resistance of a soldered joint has been reported [1]. Previous work has also addressed the effects of solder oxidation [2], interfacial reactions [3-7], fatigue [8-14], creep [15-18] and impurities [19-22].

This work investigates the effect of solder thickness (from 10 to 30 μm) on the heat transfer between two copper surfaces. Copper is used in this study due to its common usage for heat sinks and the thermal contact between a heat sink and a circuit board, for instance, is of concern in the electronic industry. The heat transfer was evaluated by using the laser flash method at room temperature [23]. The laser flash was incident on one side of the copper-solder-copper sandwich, while the temperature rise at the other side was monitored. The quicker is the temperature rise, the better is the heat transfer. Based on half of the time that it takes for the temperature to rise (i.e., the halftime $t_{0.5}$), the thermal contact conductance at a copper-solder interface was calculated.

2. Experimental Methods

2.1 Sample preparation

The solder used was the eutectic 63Sn-37Pb alloy (melting temperature = 183°C, Kester Solder, Des Plaines, IL). It was melted on the flat surface of a copper disk heated on a hot plate at about 200°C. No flux was used. The other copper disk (at room temperature) was placed on top of a molten solder. Both surfaces of the copper disks had been mechanically polished by 0.05 μm alumina powder before soldering. After placement, the solder solidified due to the cooling. The sandwich was then heated on the hot plate until the solder melted again. After melting, a pressure was applied on the sandwich in order to squeeze out some of the molten solder for the purpose of controlling the solder thickness. Then the sandwich was removed from the hot plate and allowed to cool to room temperature. The copper disks were 12.6 mm in diameter and 1.06 mm in thickness for one disk and 1.10 mm for the other disk. The solder thickness ranged from 10 to 30 μm, as measured by cross-sectional optical microscopy of a metallographic section. Because of the difficulty of controlling the solder thickness during soldering, essentially one specimen was tested for each thickness. The microscopy showed the absence of pores in the solder or at the interface between solder and copper. It also showed uniformity in the solder thickness.

2.2 Thermal contact conductance measurement

The thermal contact conductance between two copper disks sandwiching a thermal interface material was measured using the transient laser flash method [24]. The finite element program ABAQUS was used to calculate the thermal contact conductance through temperature vs. time curves, which were experimentally obtained. The calculation [24] assumed no heat transfer between sample and environment, except for the absorption of laser energy by the sample. Moreover, it assumed that the laser energy was uniformly absorbed on the surface of the sample, that the heat flow was one-dimensional, and that the thermal contact conductance between each copper disk and the interface material was uniform.

A Coherent General Everpulse Model 11 Nd glass laser with a pulse duration of 0.4 ms, a wavelength of 1.06 µm and a pulse energy up to 15 J was used for impulse heating. The laser power was adjusted to allow the temperature rise of the sample to be between 0.5 and 1.0 °C. The upper surface of the copper disk on which the laser beam directly hit had been electroplated by black nickel in order to increase the extension of laser energy absorption relative to the extension of reflection. A Type-E cement-on foil thermocouple of thickness 0.013 mm (Omega Engineering, Inc., Stamford, CT, No. CO2-E) was attached to the back surface of the other copper disk for monitoring the temperature rise. Another thermocouple of the same type was put ~ 30 cm above the sample to detect the initial time when the laser beam came out. A National Instruments DAQPad-MIO-16XE-50 data acquisition board with a data acquisition rate up to 20,000 data points per second at 16 bites resolution, along with NI-DAQ interface software coded in Visual Basic, was used to monitor the responses of both thermocouples simultaneously. Calibration using a standard graphite sample was performed before testing each sample in order to ensure measurement accuracy. The data acquisition rate used for each test was adjusted so that there were at least 100 temperature data points during the temperature rise.

The experimental error in transient thermal contact conductance measurement consists of random error due to experimental data scatter, and systematic error mainly due to the lag of the thermocouple response and partly due to the method used to calculate the conductance from the temperature data. The higher the thermal contact conductance, the greater is the error. The thermal diffusivity of a standard NBS 8426 graphite disk (thickness = 2.62 mm), which had a similar transient temperature rise time as the copper sandwich, was measured prior to testing each sample in order to determine the systematic error. The measured thermal diffusivity of the graphite was about 7% less than the reference value, which corresponds to a time lag of about 0.0006 s. Moreover, a single copper disk (thickness = 2.66 mm) was also tested and a time lag of about 0.0008 s was found upon comparison of the measured thermal diffusivity with the reference value. From multiple measurements of both copper and graphite, the time lag of the thermocouple was found to be about 0.0007 s, which was used to correct for the measured rise time for each sample. The conductance reported in Table 1 for each sample was based on the corrected rise time. The standard error of the contact conductance value was calculated based on the error of the measured thickness of solder and the error of $t_{0.5}$.

3. Results And Discussion

Table 1 shows that the greater the solder thickness in the copper-solder-copper sandwich, the larger is $t_{0.5}$ (i.e., the slower is the heat transfer). Increasing the solder thickness from 10 to 30 µm causes $t_{0.5}$ to increase by 25%.

Although the percentage change in solder thickness was large, all the solder thicknesses

Thickness of solder (μm, ± 2)	10	15	15	25	30
$t_{0.5}$ (s, ± 0.0001)	0.0060	0.0065	0.0067	0.0070	0.0075
Contact conductance (10^6 W/(m²-°C), ± 0.8)	6.2	6.0	5.0	5.0	5.5

Table 1. Solder thickness, $t_{0.5}$ and copper-solder thermal contact conductance in relation to heat flow across the thickness of a copper-solder-copper sandwich

used (from 10 to 30 μm) were near the low end of the feasible range of solder thickness. In solder application, it is difficult to control the solder thickness in this range, so a solder layer used in practice as a thermal interface material tends to have a considerable range of thickness. This thickness variation causes a substantial effect on the heat flow, as indicated by Table 1.

A 25% increase in $t_{0.5}$ can be obtained by decreasing the thermal conductivity of the thermal interface material from 68 W/(m-°C) [25] to about 14 W/(m-°C) without changing the thickness and the specific heat of the material and from 6 X 10^6 to about 2 X 10^6 W/(m²-°C), without changing the thickness of the interface material, as shown by calculation. Hence, increasing the solder thickness from 10 to 30 μm has the same effect on $t_{0.5}$ as degrading the solder-copper interface.

Table 1 shows that the thermal contact conductance of the copper-solder interface is essentially not affected by the solder thickness, as expected. The value of the contact conductance (around 6 x 10^6 W/(m²-°C)) is much higher than that previously reported (2 x 10^5 W/(m²-°C)) [24]. This is because Ref. 24 assumed zero thickness of the interface material in the calculation, whereas this work considered two copper-solder interfaces separated by solder. The calculation in this work is therefore more accurate than that in Ref. 24.

4. Conclusion

The thickness of a thermal interface material, namely solder applied in the molten state, has significant effect on the heat transfer between thermal conductor (copper) surfaces. Increasing the solder thickness from 10 to 30 μm causes a 25% increase in $t_{0.5}$, though the thermal contact conductance of each copper-solder interface is not affected. Such an increase in $t_{0.5}$ can be equivalently obtained by using a thermal interface material with a thermal conductivity that is 80% lower, while not changing the thickness or the specific heat of the interface material. It can also be equivalently obtained by decreasing the thermal contact conductance of the solder-copper interface by 70%, while not changing the thickness or specific heat of the interface material. Thus, minimization of the solder thickness is recommended in practice.

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