THERMAL PERFORMANCE OF INTERFACE MATERIAL IN MICROELECTRONICS PACKAGING APPLICATIONS

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Abstract

As the need to dissipate heat from microelectronics packaging increases, the role of thermal interface material becomes crucial to the overall performance of the package and the selection of a heat sink. Interface material is used to enhance heat transfer by reducing thermal resistance across the interface between the heat source and the heat sink, and to minimize the variance of the interface resistance as compared to just surface-to-surface contact. Experimental determination shows that the material's thermal resistance is a strong function of contact pressure. The petiormance discrepancy between application contact pressure and the pressure used in obtaining manufacturer's published data may result in an erroneous selection of interface material which may lead to a device failure due to a greater-than-expected thermal resistance. This paper focuses on the testing procedure used for measuring the thermal performance of interface material and relevant implications the test results have on material selection. The thermal performances of various interface materials are reported.

Introduction

Interface materials are used to reduce the contact resistance between the surfaces of the heat source and the heat sink. Typical interface material fills the voids and grooves created by imperfect surface finish of two mating surfaces, thus forcing air out and improving surface contact and the conduction of heat across the interface. Such heat transfer is essential for cooling high power microelectronics devices.

Numerous authors have investigated the thermal properties of interface material. Mok [1] used several materials to evaluate the case to ambient thermal resistance of multichip modules that dissipate heat through solder balls located between the chips and the silicon

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substrate. The best performing material was ZnO grease, while boron-nitride filled film and alumina filled film produced unusually high resistance because the contact pressure was not large enough to force out all the trapped air at the interface. Ouellette and De Sorgo [2] analyzed interface material by evaluating actual operational thermal performances using transistors mounted in TO-3, TO-218, and TO-220 packages. They concluded that the interface material “appeared” to be less effective than predicted by the material’s intrinsic thermal properties. The performance difference was due to mounting pressure gradients, heat density gradients, and variations in junction temperatures. De Sorgo [3] continued with the transistor packaging application analysis by studying the long term effect of material compression. He concluded that interface material only requires contact pressure to conform to the mating surfaces and pressure losses over time do not affect the performance of the material.

Understanding the test methods used to determine the thermal properties of interface materials is critical for material selection in microelectronics packaging applications. The thermal properties can be measured by either ASTM test standard D5470-93 or military specification MIL-I-49456A. Both methods are recognized throughout the industry as standards. De Sorgo [4,5] presented a similar test device used to measure thermal conductivity and thermal impedance (or resistance). High contact pressures (300 psi for ASTM and 500 psi for MIL SPEC) are used to reduce the effects of interface resistance generated by trapped air in the interface. The data gathered at high pressures is then used as the publish thermal performance characteristics.

In typical microelectronics packaging applications, the contact pressure varies between 10 to 50 psi and data provided at 300 psi will be an underestimation of material thermal resistance. Any pressure exceeding 50 psi might damage the packaging itself. To the best of authors’ knowledge, manufacturers do not publish low contact pressure data because of the case dependency of interface resistance. Therefore, to analyze the material’s performance at the application contact pressure, an interface testing apparatus has been modeled after the aforementioned two standards, but with minor modifications to measure thermal performance of interface material at low contact pressures. This paper discusses the method and the relevant implications the test results have on thermal interface material selection. A surface contact analysis is also presented to further characterize the interface resistance.

Experimental Procedure

The concept behind measuring the thermal performance of interface material is straight forward. A reference calorimeter is used to measure the heat through the material. Other calorimeters are used to create a linear extrapolation to find the temperature drop across the material surfaces. With this set of information, in addition to the cross sectional area, the thermal resistance can be calculated, using the equations summarized in Table 1.

Heat (Watts)	$Q_{Cal1,2} = k_{Cal1,2} A_{cs} m_{1,2}$
Average Heat (Watts)	$Q_{avg} = \frac{Q_{Cal1} + Q_{Cal2}}{2}$
Surface Temperature (“C)	$T_{6,7surf} = T_{6,7} \mp \frac{(T_{3,7} - T_{6,10})d_{6,7surf}}{d_{3-6,7-10}}$
Surface Temperature Difference (“C)	$\Delta T_{surf} = T_{6surf} - T_{7surf}$
Cross Sectional Area (m*)	$A_{cs} = \frac{\pi(0.5D_{Cal1} + 0.5D_{Cal2})^2}{4}$
Thermal Impedance (“C m^2/Watt)	$R_{IA4} = \frac{\Delta T_{surf} A_{cs}}{Q_{avg}}$
Variables	$k_{Cal1,2}$ = thermal conductivity of calorimeter material d_{x-y} = longitudinal distance on calorimeter, see Fig. 2 $m_{1,2}$ = slope generated by linear regression of temperature and longitudinal distance on calorimeter 1 or 2 TX= temperature measured at location x $D_{1,2}$ = diameter of calorimeter 1 or 2

Table 1: Analysis Equations

Figure 1 shows a schematic of the test apparatus constructed for this investigation. The equipment used in the interface material testing include calorimeters, heater block and guard heater, complete with heater cartridge, insulation, chiller plate, and a pneumatic press. Starting with the bottom of Figure 1, the guard heater has three cartridge heaters inside it which are connected in parallel. Between the guard heater and the heater block is a 5 millimeter thick circuit board with a FR-4 epoxy rating. This material thermally and electrically insulates the guard heater and the heater block while providing an environment that allows the heat to flow from the heater block through the specimen. The surface between the heater block at the lower calorimeter is coated with thermal grease. The specimen is located between the upper and lower calorimeter. On the top side of the upper calorimeter is the chiller plate; thermal grease is also at the interface of the calorimeter and the chiller plate, Located atop the chiller plate is the pneumatic press. Contact pressure is controlled by regulating the pressure of the compressed air to the pneumatic press. The entire column is wrapped with foam insulation to prevent radial heat loss.

The heater block and guard heater are made of copper while the calorimeters are Atuminum 6160 T6. The calorimeters are cylindrical columns with a 1 in^2 cross sectional area and the surfaces at the specimen interface have a measured mean surface roughness value of 8.9 pm. The specimen surface is cleaned with alcohol swabs and inspected to check for scratches and divots that might trap air once the specimen comes in contact with the surface. The thermal performance can be greatly deteriorated by the smallest amount of air between the interface. Finally, Type-T thermocouples are calibrated before attachment to the calorimeters. Equilibrium temperature measurements are taken once the change in temperature is less than 1 ‘C per ten minutes,

The experimental apparatus varies from the methods described by ASTM test standard D5470-93 and military specification MIL-I-49456A in two ways. First, a reference calorimeter is not used to calculate heat flux through the specimen. A least square fit is done on the data recorded from the calorimeter thermocouples to determine the heat flow through each calorimeter using Fourier’s Law of Conduction. Figure 3 shows the temperature measurements of the upper and lower calorimeters. The fit reduces the effects of heat gradients at the thermocouple location. Then, the heat flow values are averaged to determine the net flow through the specimen. Second, while both methods test interface material at high contact pressure, the current test apparatus can vary contact pressure, enabling low pressure measurements, via a highly accurate and precise air regulator.

Material Description

Material A, named Kon-Dux™, is a gray, non-woven fibrous compound consisting of graphite and oil. The material is pressed together and then rolled for delivery. It can be cut into a variety of shapes by using a knife or punch die. This material is easy to work with, but has some problems associated with specimen preparation. First, the material is usually delivered in large rolls. This method of delivery caused defects like crease lines and surface depressions which changes material microstructure and increases thermal resistance. Secondly, the material is also easy to rip. When cutting a specimen, special care must be taken to protect the cutting edge from fraying. If the edge begins to fray, it can be cleared up by gently scraping off the frayed edges. There is a possibility of the material ripping under the template if care is not taken.

Material B, named A-Dux™, is a white silicone based material used primarily to eliminate problems associated with thermal grease such as contamination of reflow solder.

It is highly compressible and compliant, mating closely with companion surfaces by filling voids created by uneven or warped surfaces. It provides a thermally conductive intetiace where electrical isolation is not required. This material is available with an adhesive on one or both sides and in different sheet sizes. It can be cut into a variety of shapes by using a knife or by using a punch die. When cutting with a knife a stiff clear plastic release paper on one side must be removed.

Material C is a white material which uses a highly compressible, elastic carrier for floroether oil. The material is distributed in small sheets with release paper on front and back. Special care must be taken when using the material, because it is highly elastic. The material is likely to stretch when removing one piece of release paper. It is not easy to cut with a knife and cannot be cut with a punch die because of its elasticity. When cutting, score the material several times before attempting to cut through. Once the sample is cut, very special care must be taken for handling. Once removed from the release paper, the material loses its rigidity and will likely fold onto itself, rendering the sample unusable because it will stretch and deform. If the material is cut using a sample calorimeter as a template, the sample should be cut slightly larger that the template to compensate for material shrinkage. The material shrinks when removed from either the template or the release paper.

Results and Discussion

To accurately acquire thermal resistance data from a variety of interface materials, tests were repeated using samples taken from different batch sheets to ensure manufacture consistency. Six samples of each material were analyzed. The results are plotted in Figure 4 with range bars, and the average thermal performance of the four materials and the bare surface case appear in Table 2.

Figure 4 shows the thermal resistance as a function of contact pressure. As expected, the resistance decreases as the pressure increases. Generally, the resistance at low application pressure was three times the published manufacturer's data. All the materials perform better than the bare surface contact except for Material B. This is a result of thickness variation between manufacturer's and measured data. The material tested was 50% thicker than specified by the manufacturer. An assumption was made that the resistance would be **50%** greater based on the linear relationship between material thickness and thermal conductivity.

Materials A and C help to significantly reduce the interface resistance at low contact pressure compared to high pressures. Thermal grease shows the lowest resistance and its petiormance is virtually independent of the contact pressure. Interface material can be compared to see which provides the lowest resistance relative to application pressure, material handling, cost and availability.

Interface Material			Thermal Resistance (“C in^2/W)							
				Contact Pressure (psi)						
. Type	Description	Thickness (in)	Mfg. Data	8	36	71	106	141	175	350
A*	graphite and oil sheet	0.005	0.17	0.62	0.58	0.38	0.29	0.28	0.25	0.20
B[3]	silicone sheet	0.006[4]	0.75	1.81	1.72	1.60	1.40	1.25	1.18	0.80
C[5]	floroether oil sheet	0.007	n/a[6]	1.10	0.98	0.84	0.71	0.67	0.65	0.44
Grease[7]	synthetic grease	n/a	0.19	.274	.206	.200	.193	,194	.193	.180
Bare Calorimeter Surfaces		nla	n/a	1.74	1.57	1.23	1.08	0.89	0.83	0.53

Note: **n/a means not available** or not **applicable.**

Table 2: Thermal Performance of Interface Material.

The bare surface measurements serve as a baseline for interface material comparison. The measurement is only valid for these two particular calorimeters because of uniqueness of their surface flatness and roughness. For conforming rough surfaces, the surface-to-surface contact resistance can be estimated using the following equation[6]:

$$\frac{1}{R_j} = \frac{1}{R_c} + \frac{1}{R_g}$$

where R_j is the total joint contact resistance with the conduction resistance through the intimate solid contacts between mating surfaces R_c and the gap resistance through the interstitial fluid R_g determined from

$$\frac{1}{R_c} = 1.25 \frac{k_s A m}{\sigma} \left(\frac{P}{H} \right)^{0.95}$$

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[2] Aavid Thermal Technologies product KON-DUX™.

[3] Aavid Thermal Technologies product A-DUX™.

[4] thickness quoted at 0.004 in by the manufacturer; it is assumed that the thicker sample has a proportional increase in thermal resistance.

[5] commercially non-available material.

[6] manufacturer's data unavailable at time of printing.

[7] Aavid Thermal Technologies product SIL-FREE™.

$$\frac{1}{R_g} = \frac{k_f A}{Y + \sigma M}$$

where k_s is the harmonic mean solid conductivity, k_f the interstitial fluid conductivity, P the apparent contact pressure, H the hardness of the softer solid, σ the RMS surface roughness, m the mean asperity slope, and A *is* the apparent surface area. For air, the gas rarefaction parameter M = 0.081, and the distance between mean planes of the contacting surfaces, Y, is given as

$$Y = 1.53\sigma\left(\frac{P}{H}\right)^{-0.097}$$

The resistances, R_c, R_g and R_j are calculated using the above correlations and compared in Table 3 with R_{exp} measured for the bare surface case. As can be seen from the table, R_{exp} *is* an order of magnitude greater than the computed R_j, but always less than the gap resistance R_g, indicating that the surfaces were not flat, and the interface must had **a** substantial area being covered with air entrapments. This is further evidenced by the trend of R_{exp} which is typical of non-flat surface contacts. At a low pressure of 8 psi, R_{exp} is nearly equal to R_g, indicating that only a small portion of the surface area experienced intimate contact. As the applied pressure increased, it is expected that a greater portion of the area will be in contact as the surfaces go through an elastic deformation. Consequently, the resistance will fall closer to that of the conforming rough surfaces, as shown in Table 3.

Applied Pressure	**Thermal Resistance (°C in²/W)**			
(psi)	R_c	R_g	R_j	R_{exp}
8	0.663	2.178	0.509	1.74
36	0.159	1.888	0.147	1.57
71	0.083	1.771	0.080	1.23
106	0.057	1.705	0.055	1.08
141	0.043	1.660	0.042	0.89
175	0.035	1.626	0.035	0.83
350	0.018	1.523	0.018	0.53

Table 3: Computed and Measured Thermal Resistances
for Bare Surface Contact

Materials A and C help to significantly reduce the interface resistance at low contact pressure compared to high pressures. Interface material can be compared to see which provides the lowest resistance relative to application pressure, material handling, cost and availability.

The effects of interface resistance are large at low contact pressure, and they will be equivalently large in microelectronics packaging applications where typical contact pressure ranges from 10 to 50 psi. The magnitude of the resistance will vary as a function of contact pressure, surface finish, and interface material. Also, the larger area of the interface material, the greater the chance of trapping air when applying the material to the surfaces. Any trapped air will result in an increase of interface resistance.

Conclusion

The results show that data collected at high contact pressure does not provide an accurate representation of interface material resistance in the pressure range typically observed in microelectronics packaging applications. The measured results at low pressures are approximately three times the published values. Material thermal performance will be affected by surface finish, contact pressure, and application properties. Any trapped air in the application of the interface material will result in an increase in thermal resistance.

Acknowledgment

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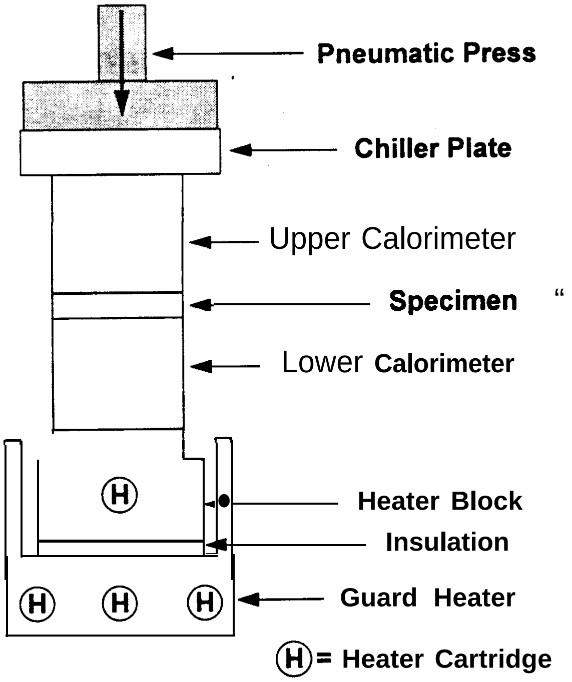

Figure 1: Experimental Apparatus Used to Measure Thermal Performance of Interface Material.

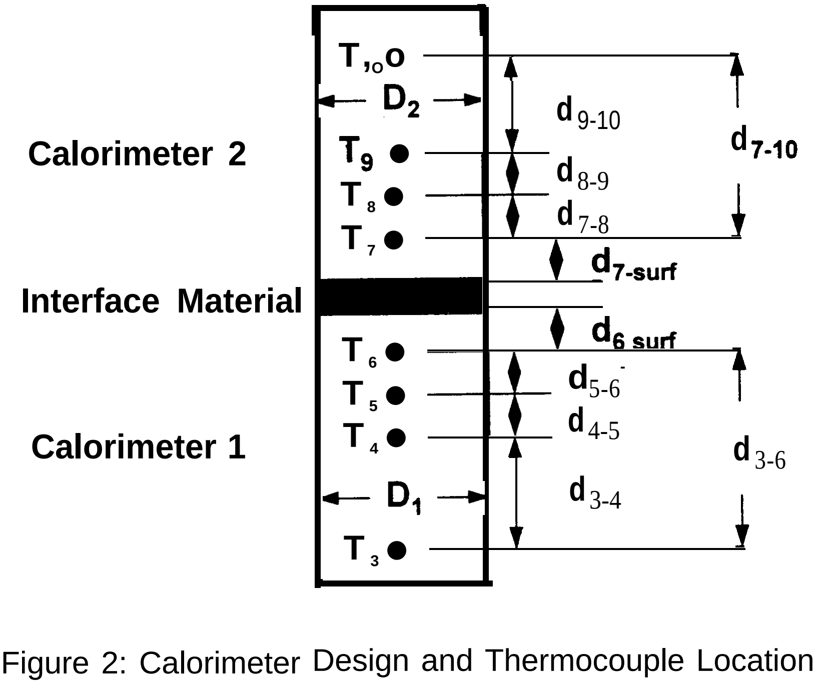

Figure 2: Calorimeter Design and Thermocouple Location.

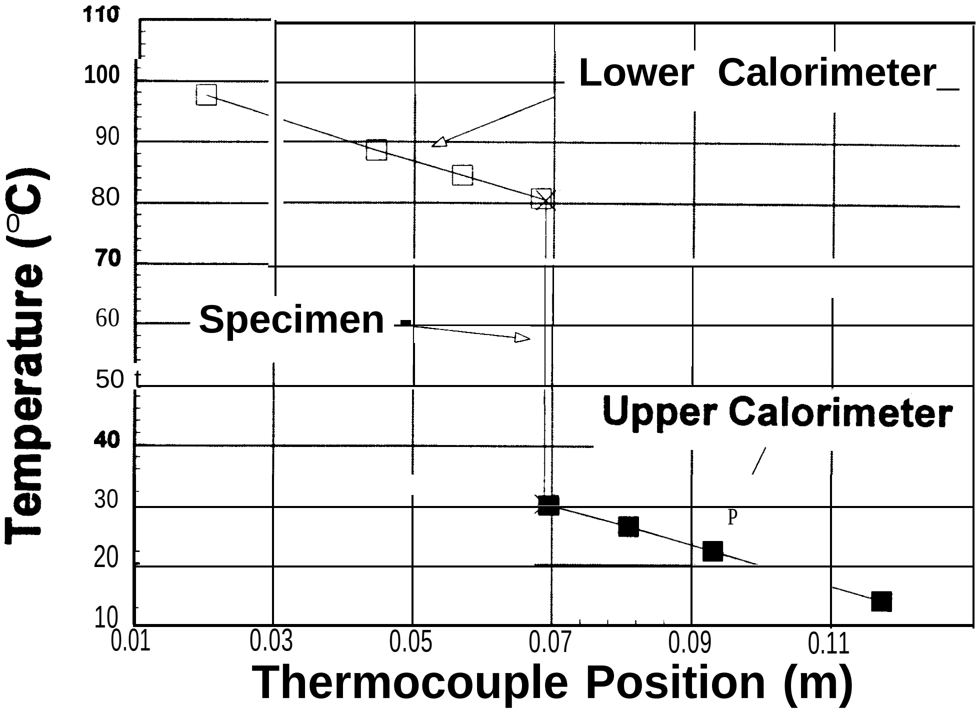

Figure 3: Temperature Distribution across Upper and **Lower Calorimeter and Through the Specimen.**

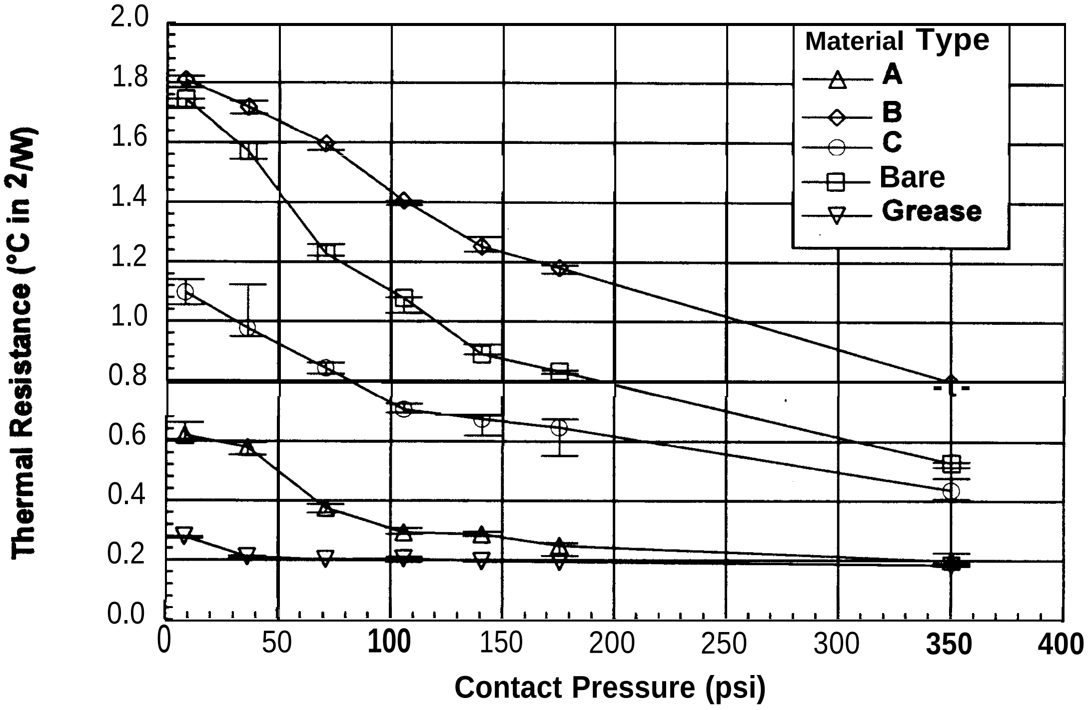

Figure 4: Thermal Performance of Various Interface Materials