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Thermal Contact Conductance of Adhesives for Microelectronic Systems

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Adhesives, which are often used to attach a silicon device to a heat spreader or ceramic substrate, generally increase the heat transfer across the material junction and improve the thermal contact conductance. This investigation evaluated the effect of RTV and epoxy adhesives and high-temperature cements on the thermal contact conductance between aluminum 6106-T6 and aluminum 356-T61. The thermal contact conductance was evaluated at mean interface temperatures of 25 and 60°C (77 and 140°F) and at pressures ranging from 345 to 2756 kPa (50 to 400 psi). The thermal contact conductance values of these adhesives were not significantly affected by variations in specified interface temperature or pressure, however, adhesive thickness and thermal conductivity were influential in the measured conductance.

Nomenclature

D_q = asperity slope
F = flatness
h = thermal contact conductance
h^* = dimensionless thermal contact conductance
k = thermal conductivity
R_a = average surface roughness
R_q = rms surface roughness
T = temperature
TIR = true indicator reading
t = thickness of applied adhesive
W_a = average surface waviness
σ = rms roughness

Subscripts
a = adhesive
b = bare surface
g = glass transition
s = harmonic

Introduction

THE thermal performance of electronic systems and devices, and the adhesives used to mount the devices, has become extremely important. Experimental studies related to the thermal conductance of adhesives employed in microelectronic packaging are very limited. There may exist experimental data obtained by major microelectronic companies, however, these data are often proprietary and remain unpublished.

Bolger[1] conducted an experimental investigation to determine the thermal conductivity of a series of adhesives in which the filler was the only variable. Heat-cured epoxy tape adhesives were made with such fillers as diamond powder, silver, aluminum, and alumina. The paper concluded that the thermal conductivity of diamond filled adhesives is comparable to BeO filled adhesives, but superior to AlN, Al_2O_3, BN, ZnO, or other dielectric adhesives. Further, the thermal conductivity of diamond filled adhesives is lower than the best filled silver, aluminum, or copper adhesives.

Nguyen et al.[2] reviewed the recent developments of cyanate ester-based die attach materials that were designed for use in hermetic and plastic packaging. Polycyanate-based die attach material that was introduced in 1992 can be utilized with standard die bonders and has rapid cure capability and exceptionally low moisture outgassing. The review concluded that cyanate polymers have proven to be reliable for ceramic packaging because the material produces low volatile by-products and can withstand high temperatures while maintaining polymer toughness.

Ikemura et al.[3] performed an experimental study of multilayer film adhesives for integrated circuit packaging applications. Multilayer adhesives are fabricated with a silver-filled epoxy and low T_g rubber combinations. The total thickness of the two multilayer (four layers) adhesive systems investigated was 25 μm. The first multilayer system (NML-1) consisted of three layers of silver-filled epoxy and one layer of low T_g rubber, and was nonconductive. The second multilayer (NML-2) system consisted of three layers of silver epoxy and a fourth layer of silver-filled low T_g rubber and was conductive. The paper concludes that both multilayer systems show good thermal conductance characteristics.

Peterson and Fletcher[4] conducted an experimental investigation to determine the magnitude of the thermal contact resistance that exists at bonded joints between silicon chips and the substrate materials used in electronic packages. Several thermally conductive epoxies with thermal conductivities ranging from 0.27 to 1.92 W/m K were placed in contact with ground aluminum 6061-T6 surfaces. The results of the experimental study indicated that the thermal contact resistance at the chip/bond and bond/aluminum interfaces is a significant factor in the determination of the overall joint resistance. The experimental investigation determined that mean interface temperature had little influence on thermal contact resistance.

Peterson and Fletcher[5] conducted a subsequent experimental investigation to determine the significance and magnitude of the thermal contact conductance occurring at the interface of mold compounds and substrate/spreader materials. The study consisted of four mold compounds and three heat spreader materials that were evaluated over a range of interface temperatures and pressures. The experimental data for thermal contact conductance remained fairly constant with respect to interface temperature; however, changes were significant with respect to variation in interface pressure.

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There is a lack of sufficient data on the thermal contact conductance of adhesives used in electronic packaging. Considering the importance and usefulness of these data, more experimental studies are needed to determine these values. Therefore, the main objectives of this investigation were to measure the thermal conductance of several commercially important die attach adhesives and to develop a correlation based on the experimental data for use in predicting thermal conductance values. These results can have a significant impact for thermal design engineers within the microelectronic and spacecraft industry.

Experimental Program

To provide additional information on the thermal conductance of adhesive materials, an experimental investigation was conducted. A brief description of the experimental facility and experimental procedure is presented, whereas a more detailed description can be found in a previous investigation conducted by Marotta and Fletcher.[6]

The experimental test facility used in this investigation incorporated a vertical column consisting of a frame with sliding plates for the support of two combination heat source/sink specimen holder assemblies, the test samples, a load cell, and pneumatic bellows. The vertical test column was composed of aluminum 6101-T6 upper and lower fluxmeters and a center aluminum 356-T61 sample. The diameters of the fluxmeters and sample were 2.54 cm (1.0 in.) and the lengths were 11.43 cm (4.5 in.) and 3.81 cm (1.5 in.), respectively. Thermal grease (Dow Corning 340-Silicone Heat Sink Compound) was applied between the sample surface and the upper fluxmeter. Each adhesive coated specimen had five thermocouples located at its center that were evenly spaced at 0.00635-m (0.250-in.) intervals from the surface. In addition, both aluminum 6101-T6 fluxmeters had five thermocouples that were located at 0.00635-m (0.250-in.) intervals.

Since the surface profile has an effect on the measured thermal conductance, all surfaces were characterized utilizing a Federal Products Surfanalyzer 5000/400. In addition, a complete surface characterization was conducted, including rms surface roughness, average and rms waviness, and the overall flatness deviation. Table 1 provides details on the surface characteristics.

Experimental Procedure

Prior to the application of the adhesives on the surface of the aluminum 356 sample, bare junction thermal contact conductance tests were performed at interface temperatures of 25, 60, and 80°C (77, 144, and 176°F, respectively), whereas the pressures were varied from 172.25 to 1378 kPa (25 to 200 psi).

The initial adhesive tested was RTV 566A with a curing agent (RTV 566B) in the ratio of 100 g to 129 μl. To control the bond line, the elastomer (RTV 566A) contained approximately 0.05%, by weight, of 0.124-mm glass beads. The surface preparation involved Methyl Ethyl Ketone (MEK) wipe, MEK scotch brite scrub, and priming. The second adhesive tested was Metalbond 1146 (a film adhesive), bonded similarly, except glass beads were not employed. In addition to the RTV 566A and Metalbond 1146, four Norcast epoxies (3230 LV, 3230 LVF, 3230 KT, and 3230 HT) were tested. Prior to the application of these epoxies, 0.05%, by weight, of 0.124-mm glass beads were added and the mixture degassed. Omegabond 101 and 200 were then tested and their bonding was again similar to Metalbond 1146.

A two-part silver epoxy followed the two Omegabond materials. The two parts were mixed in equal proportions by weight and applied to the surface. High-temperature cements such as Omegabond 300 and 400 were then tested with the thickness of the applied adhesives ranging from 0.026 to 1.549 mm, as shown in Table 2.

The order in which each adhesive was tested had no significance. Each adhesive was randomly chosen or may have been received prior to the other adhesive. It must be noted that each aluminum surface was cleaned thoroughly with MEK wipe, methanol, and acetone prior to the application of the next adhesive when fluxmeters were reused. In this manner, cross contamination with prior adhesives was minimized.

Because of the small bond thickness, the adhesives employed were not instrumented with thermocouples. The reported thermal conductance data are for the case of heat flux passing from the aluminum 356-T6 sample through the adhesive to the aluminum 6101-T6 fluxmeter. The experimental tests were conducted at mean interface temperatures of 25 and 60°C (77 and 140°F, respectively) and the interface pressures ranged from 345 to 2756 kPa (50 to 400 psi).

Uncertainty Analysis

The uncertainty involved in the various parameters and quantities used to compute the thermal contact conductance can be combined to arrive at one overall relative uncertainty value. The Kline and McClintock[7] method was employed to determine this overall relative uncertainty in the thermal conductance.

The total average overall uncertainty of the thermal conductivity of each base aluminum material is 2.5%. This value is composed of the accumulation of the uncertainty in the thermal conductivity of the NIST (National Institute of Science and Technology) iron fluxmeters (1.5% at 95% confidence level), the temperature reading of the special limit of error thermocouples (1.1 C or 0.4% above 0°C), thermal temperature gradients within the iron fluxmeters, location tolerance of the thermocouple holes, and the dimensional tolerance for the cross-sectional area (0.6% total).

The average overall uncertainty in the thermal contact conductance for each adhesive was the accumulation of the uncertainties mentioned for the thermal conductivity with the addition for uncertainty resulting from the temperature difference across the adhesive junction. This average uncertainty in thermal conductance was 9.00%.

Results and Discussion

The thermal contact conductance results of the adhesives tested are presented as a function of apparent pressure that encompass the range of temperatures [25 and 60°C (77 and 140°F) and pressures [345–2756 kPa (50–400 psi)] commonly encountered in the electronic, spacecraft, and telecommunication packaging industries.

Table 1 Metrology data for aluminum 6101-T6 fluxmeters and aluminum 356-T61 samples

	R_{a}, μm	R_{q}, μm	W_{a}, μm	D_{q}, μm	F, μm
Fluxmeter number					
1	0.50	0.60	4.00	0.017	23.6
2	0.40	0.60	4.90	0.019	28.8
3	0.26	0.34	2.90	0.005	18.3
4	0.80	1.00	4.20	0.018	29.0
5	0.60	0.70	2.20	0.015	22.8
6	0.60	0.80	1.60	0.012	14.8
7	0.78	0.99	0.63	0.004	11.7
8	0.40	0.70	0.70	0.011	8.4
9	0.60	0.70	0.70	0.010	8.8
10	0.60	0.70	0.70	0.011	8.4
Sample number					
1	0.30	0.40	1.90	0.015	17.6
2	0.50	0.70	1.70	0.017	40.2
3	0.30	0.50	1.91	0.012	10.4
4	0.37	0.49	2.36	0.005	19.1
5	0.36	0.49	1.46	0.004	13.6
6	0.30	0.40	0.70	0.013	14.4
7	0.30	0.38	1.49	0.004	20.3
8	0.33	0.43	2.17	0.005	17.9
9	0.20	0.30	1.90	0.014	17.0
10	0.43	0.58	1.49	0.005	13.8

Table 2 Thermophysical properties, curing time, and thickness of adhesives

Number	Product designation	Fluxmeter number/ sample number	Thermal conductivity, W/m K	Specific gravity	Coefficient of thermal expansion, m/m/°C	Curing time and temperature	Adhesive thickness, mm	Application requirements and characteristics
	Silicone							
1	GE silicone RTV 566[a]	1/5	1.15	1.49	——	7 days, room temperature	0.074	Excellent adhesion capability with primer, good release properties, and cures at room temperature.
	Epoxies							
2	Metalbond 1146[b] (BASF 1146)	2/2	1.42	——	——	1 h, 120°C	0.026	Film adhesive that possesses good toughness, hot/wet strength, and environmental durability.
3	Norcast 3230 LV[c]	4/4	1.43	2.0	14×10^{-6}	3 h, room temperature	0.584	Highly viscous potting and casting compound, useful at low and high temperature.
4	Norcast 3230 LVF[c]	6/3	1.43	2.0	14×10^{-6}	3 h, room temperature	0.620	Designed for encapsulating applications. Low viscous version of 3230.
5	Norcast 3230 KT[c]	5/6	4.32	2.0	14×10^{-6}	3 h, room temperature	1.016	High thermal conductivity and wide temperature range of application.
6	Norcast 3230 HT[c]	5/6	4.32	2.0	14×10^{-6}	3 h, room temperature	0.512	Low viscous version of 3230 KT, high flexural strength, and high thermal conductivity.
7	Omegabond 101[d]	4/4	1.03	——	20×10^{-6}	1 day, room temperature	0.381	Versatile, high thermally conductive epoxy designed to permanently bond.
8	Omegabond 200[d]	3/7	1.38	——	21×10^{-6}	8 h, 120°C	0.355	High-temperature, high thermally conductive epoxy, which bonds sensors to most materials.
9	Silver epoxy[e]	7/1	5.80	——	——	1 day, room temperature	0.353	Two-part adhesive for chip and substrate bonding.
	Cements							
10	Omegabond 300[d]	8/8	0.73	——	6.2×10^{-6}	1 day, room temperature	1.327	Relatively low thermal conductivity and coefficient of thermal expansion.
11	Omegabond 400[d]	9/9	1.58	——	13.0×10^{-6}	1 day, room temperature	1.448	Higher thermal conductivity and coefficient of expansion. High maximum temperature rating.
12	Omegabond 500[d]	10/10	1.42	——	10.9×10^{-6}	8 h, 60°C	1.549	Withstands short-term immersion in molten metal. Used as coating on thermocouple tubes.

[a]Manufactured by General Electric Company. [b]Manufactured by CYTEC Engineering, Inc. [c]Manufactured by R. H. Carlson Company, Inc. [d]Manufactured by Omegabond Technologies Company. [e]Manufactured by AI Technology, Inc.

Thermal Contact Conductance

The thermal contact conductance results for RTV 566, Metalbond 1146, and Norcast adhesives at two interface temperatures as a function of apparent contact pressure are shown in Fig. 1. The RTV 566 had a conductance value of approximately 4000 W/m^2 K, whereas the conductance value of Metalbond 1146 (BASF 1146) adhesive was approximately 18,500 W/m^2 K. The thickness is a factor of 3 lower than the RTV 566 adhesive, this explains the significantly higher thermal contact conductance values. However, both adhesives showed no variation in thermal conductance over the range interface temperatures and pressures.

Figure 1 also shows bare junction conductance results and indicates that below 700 kPa the thermal conductance values of the bare junction are below that of the RTV 566, whereas above 700 kPa, the thermal conductance values are greater than the RTV 566 adhesive. This may be because that with increasing pressure, the coating thickness of the RTV 566 remains fixed because of the glass spheres present. On the other hand, for the bare junction, an increase in pressure causes further deformation of surface asperities, which leads to increased thermal conductance values. The Norcast epoxies had thermal conductance values ranging from 1000 to 2800 W/m^2 K. Norcast 3230 HT possesses higher thermal conductivity than Norcast 3230 LV and 3230 LVF, and hence, higher thermal conductance for approximately similar thicknesses.

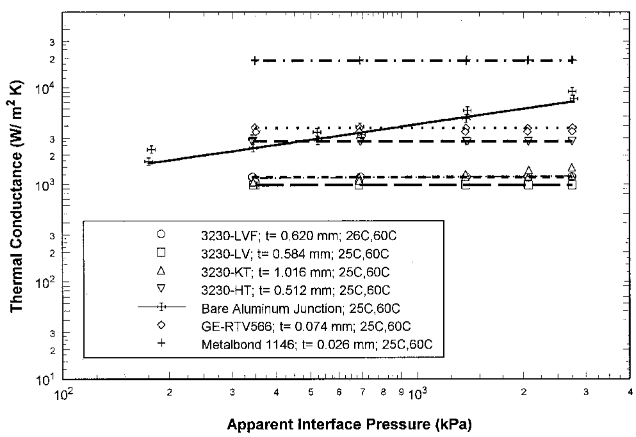

Fig. 1 Thermal contact conductance of RTV and epoxy adhesives as a function of apparent contact pressure.

The thermal conductance values for Omegabond epoxies (101 and 200) and silver-filled epoxy are shown in Fig. 2. Omegabond 101 resulted in thermal conductance values of 1500 W/m^2 K, while Omegabond 200, which possesses a slightly higher thermal conductivity value, had thermal conductance values of 2900 W/m^2 K. The silver-filled epoxy had

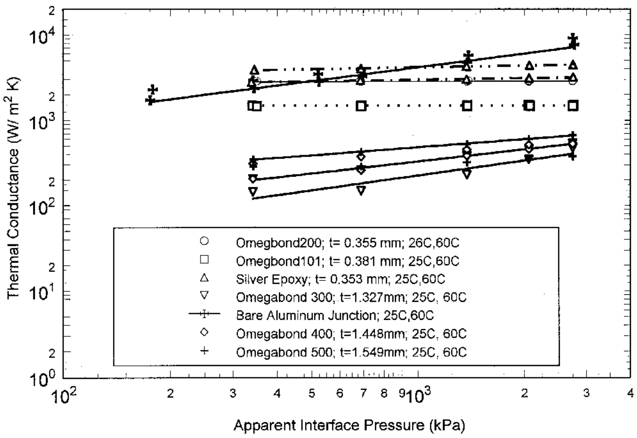

Fig. 2 Thermal contact conductance of epoxy adhesives and high-temperature cements as a function of apparent contact pressure.

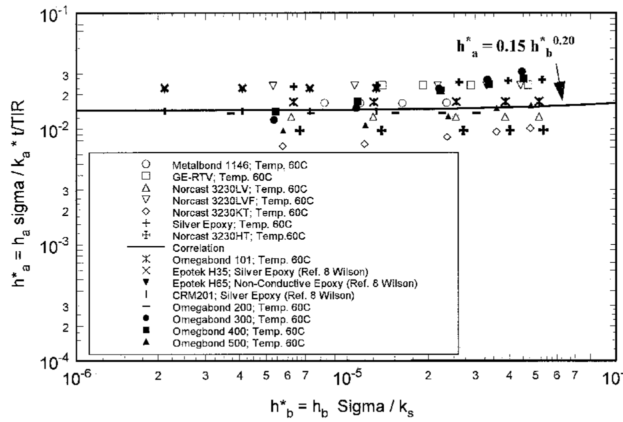

Fig. 3 Variation of the dimensionless thermal contact conductance for adhesives and cements as a function of the dimensionless thermal contact conductance for bare metallic surface.[8]

thermal conductance values that ranged from 2800 to 4460 W/m^2 K. The data clearly show a dependence on interface temperature with slight dependence on interface pressure.

Figure 2 also shows the thermal conductance values of the Omegabond high-temperature cements as a function of interface pressure. The results indicate an increase in thermal conductance values with increasing interface pressure (maximum increase of 372% for Omegabond 300) and slightly higher values with increase in interface temperature. This increase may be because of filler compression, which may cause greater filler to the matrix contact area or a decrease in cement thickness. It must be noted that because there was no influence on thermal conductance at different interface temperatures for some adhesives, the experimental data in Figs. 1 and 2 may overlap.

Dimensionless Conductance Correlation

A dimensionless thermal conductance correlation for the various adhesives measured as a function of dimensionless thermal conductance for bare surfaces is shown in Fig. 3. The dimensionless thermal conductance parameter h_a^*, for the various adhesives, incorporates the thickness and thermal conductivity of the adhesive material along with the ratio of surface roughness $\boldsymbol{\sigma}$ to overall bare surface profile flatness, TIR. The dimensionless bare thermal conductance parameter h_b^* incorporates the bare surface roughness (rms) with the harmonic mean thermal conductivity of the two base aluminum materials employed in the study. The asperity slope was not included, since for nonflat surfaces this parameter has only a limited effect on thermal contact conductance.

The correlation of h_a^* as a function of h_b^* clearly indicates that the conductance is not a function of apparent contact pressure, as observed in Figs. 1 and 2 for the adhesives tested. This may be caused by the very low thermal conductivity of the adhesives and whether or not the materials completely coat the two surfaces and maximize area coverage. The use of the ratio of surface roughness to surface profile flatness to nondimensionalize the adhesive thermal contact conductance was incorporated to address the nonideal surface flatness that exists. This factor of nonideal flatness will cause the adhesive thickness to vary along the surface profile, thus causing slight variations in local adhesive thermal conductance values.

The correlation developed for these experimental results is

$$h_a^* = 0.15 h_b^{0.20}$$

with the dimensionless adhesive thermal conductance defined as

$$h_a^* = (h_a \sigma / k_a)(t / \mathrm{TIR})$$

and the dimensionless bare metal thermal contact conductance defined as

$$h_b^* = h_b \sigma / k_s$$

The average rms percent difference between the predicted adhesive thermal conductance and the measured adhesive thermal conductance is 53%, with the inclusion of Norcast 3230KT epoxy and Omegabond 300. The average rms percent difference decreases to 31% between the predicted and measured adhesive thermal conductance values, when the Norcast 3230KT epoxy and Omegabond 300 are not considered. These particular adhesives (Norcast 3230KT and Omegabond 300) have a very high loading fraction (filler material), which may cause them to act differently when compared to the other epoxies. The differences with Norcast 3230 KT and Omegabond 300, when compared to the other epoxies, can be observed by the increasing thermal conductance values with increasing apparent contact pressure, while the other epoxies were invariant to pressure changes.

Conclusions and Recommendations

This paper provides a comparative study of the thermal contact conductance for a wide range of adhesives (elastomer, epoxies, and high-temperature cements) encountered in microelectronic systems. The experimental data indicate that the thermal conductance of a majority of these adhesives do not change significantly with variations in temperature and apparent pressure (within the range tested). Although its not explicitly shown, for a given thickness of applied adhesive, the thermal conductivity of the adhesive may have the largest influence on the thermal conductance.

A correlation was developed that may be used as a first approximation to assist thermal design engineers in determining thermal conductance for various adhesives. Prior to this correlation and experimental study, very little data existed for these classes of materials.

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