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EFFECTIVE THERMOPHYSICAL PROPERTIES OF THERMAL INTERFACE MATERIALS: PART II EXPERIMENTS AND DATA

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ABSTRACT

A new method for determining effective thermal conductivity and Young's modulus in thermal interface materials is demonstrated. The method denoted as the Bulk Resistance Method (BRM) uses empircal thermal resistance data and analytical modeling to accurately predict thermophysical properties that account for in-situ changes in material thickness due to external loading and thermal expansion.

The BRM is demonstrated using commercially available sheets of Grafoil GTA[1]. Tests were performed on thermal joints consisting of two Al 2024 machined surfaces with layers of Grafoil GTA in the interface. Test conditions included a vacuum environment, 0.2 - 6.5 MPa contact pressure, a nominal $50\,^{o}C$ mean interface temperature and a continuous loading and unloading cycle.

Test results indicated that the BRM consistently predicted thermal conductivity independent of the number of layers tested and that the predicted results were significantly lower than values reported using conventional ASTM test procedures.

NOMENCLATURE

a	$=$	linear fit coefficient (slope)
BRM	$=$	Bulk Resistance Method
b	$=$	linear fit coefficient (intercept)
E	$=$	Young's modulus (MPa)

[1]Grafoil and GTA are trademarks of Graftech Inc.

k	$=$	thermal conductivity (W/mK)
m	$=$	asperity mean absolute slope (rad)
P	$=$	contact pressure (MPa)
Q	$=$	heat transfer rate (W)
R	$=$	thermal resistance (K/W)
RMS	$=$	root mean square
RTD	$=$	resistance temperature detector
r	$=$	specific thermal resistance (m^2K/W)
T	$=$	temperature (K)
TIM	$=$	thermal interface material
t	$=$	thickness (m)
ΔT_j	$=$	joint temperature drop (K)
ν	$=$	Poisson's ratio
σ	$=$	RMS roughness (m)

Subscripts

b	$=$	bulk
c	$=$	contact
f	$=$	final
j	$=$	joint
l	$=$	lower
m	$=$	thermal interface material
o	$=$	initial
u	$=$	upper

INTRODUCTION

A wide range of thermal interface materials in the form of sheets (polymers, flexible graphite-based materials) are commonly used in microelectronics cool-

ing. The thermal performance of these interface materials strongly depends on material thermal conductivity, hardness and compliance to the contacting surface. Therefore, the reliable measurements of these properties are necessary for proper assessment of TIM and their industrial application.

It was shown in the first part of this study by Savija et al. [1] that the standard ASTM procedure for determining material conductivity has some disadvantages and generally overestimates the material conductivity. A new method for determining effective material conductivity and Young's modulus, denoted as the Bulk Resistance Method (BRM) was developed. Two Bulk Resistance Methods were presented, the Simple Bulk Resistance Method that considers only material thickness before loading, and the more accurate General Bulk Resistance Method that includes additional parameters, such as surface characteristics and thermophysical properties of the contacting solids. Both methods predict *in situ* thickness as a function of load.

In this second part of the study the application of BRM will be demonstrated and the thermophysical properties of the Grafoil GTA thermal interface material will be determined. Since the BRM is based on experimentally determined thermal resistance data, an extensive experimental investigation was conducted with Al 2024-Grafoil GTA-Al 2024 joints at pressures from $0.2\,MPa$ to $6.5\,MPa$. The TIM was tested as a single or multi-sheet stack, providing the wide range of material thickness.

Thermal resistance data for each tested specimen will be presented and discussed. Applying the BRM the effective material properties will be determined. Also, the thermal conductivity values will be averaged and compared to the results of the ASTM procedure, applied to the same thermal resistance data. As described in the first part of the study the final material thickness will be predicted and compared to the measured thickness in order to verify the Bulk Resistance Method.

EXPERIMENTAL INVESTIGATION

The experimental facility used in the experimental part of this study, shown in Fig. 1, is described in detail by Savija [2] and Culham et al. [3]. The test column consisted of heat flux meters made from aluminum 2024-T3511. The contacting surface characteristics are measured with the Surtronic 3+, Rank Taylor Hobson Limited profilometer: $\sigma = 0.27\,\mu m$, $m = 0.036\,rad$ and waviness is $0.6\,\mu m$. Ten ceramic RTD elements measured the cross-section planar temperature of the heat flux meter blocks. A sheet of thermal interface mater-

ial was placed between the aluminum blocks.

The maximum generated heat power of $50\,W$ was supplied to the test column with four Omega CIR high density cartridge heaters in the copper heating block under the lower heat flux meter. They were powered by a 30 V GPS-3030-D Instek DC power supply. The heat loss from the heater block was reduced by using an insulating phenolic plate between the heating block and the base plate. The upper heat flux meter was directly cooled by a copper cooling block and glycol-water fluid from a Haake K constant-temperature bath.

The experiments were conducted in a vacuum under a Labglass vacuum bell jar. A vacuum level of $4\,Pa$ was provided by the mechanical WELCH dualseal vacuum pump (Model 1402). A maximum axial force of $4.5\,kN$ was applied to the test column using an Industrial Devices Corporation linear actuator and special lever arm structure providing a maximum interface pressure of $6.5\,MPa$. This assembly provided continuous loading measured by a Sensotec $4.5\,kN$ load cell. A Keithly 2700 data logger with 40 analog inputs, 20 analog outputs and two digital I/O channels was used for data acquisition. The tests were fully automated using a personal computer and a LabVIEW[2] software interface.

Test Specimen Preparation

Sheets of graphite based interface material, Grafoil GTA, were cut into $25\,mm \times 25\,mm$ test specimens. Care was taken to prevent fraying of the cut Grafoil GTA sheet edges. Three nominal Grafoil thicknesses were tested: $0.127\,mm$ (GTA 005), $0.381\,mm$ (GTA 015) and $0.762\,mm$ (GTA 030). The initial thickness of the specimens was measured using a Mitutoyo digimatic outside micrometer. The surface parameters of each specimen, i.e. roughness, mean asperity slope and waviness shown in Table 1, were measured with the Surtronic 3+, Rank Taylor Hobson Limited profilometer.

Experimental Procedure

The thermal joint resistance was measured over the contact pressure range $0.2 - 6.5\,MPa$ in a continuous loading-unloading cycle. The nominal temperature of the joint was maintained at $50\,^oC$ with a 2% convergence limit. The changes in the joint temperature, heat rate and thermal resistance were monitored and used as the steady state criteria. When the ratio of the slope of the last ten readings for each parameter was not greater than 0.001% of the last measured value, the steady state was reached. After the steady state was reached at one load, the next load was automatically applied while the pressure convergence criterion

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[2]LabVIEW is a registered trademark of National Instruments Corporation.

was 1%. The heat balance between the flux meters was within 2% at steady state, attained in a $20 - 30\,min$ interval, while for the initial loading, steady state was reached in $2 - 3\,h$.
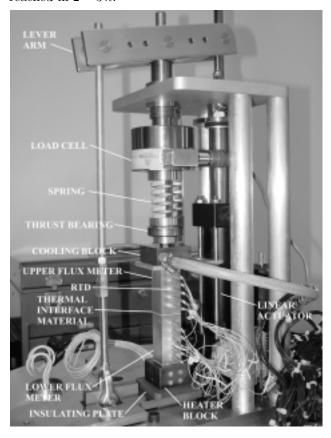

Figure 1:   Photograph Showing Detailed Rig Parts

The measured temperature distribution in the heat flux meters was linearly extrapolated at the upper and lower interface surfaces and obtained temperatures T_u and T_l were used to calculate the temperature drop at the joint $\Delta T_j = T_l - T_u$. Incorporating the temperature gradient in each heat flux meter and known Al 2024 conductivity as a function of temperature (Touloukian [4]) heat flow rates are easily calculated using Fourier's heat conduction equation. The average of the heat flow rates through the upper and lower heat flux meter, Q, was used in thermal resistance calculation: $R_j = \Delta T_j/Q$.

Experimental Error

The overall uncertainty of the experimental results is calculated using the method described by Moffat [5]. The uncertainty in the measured thermal resistance was determined from the calculated uncertainties in heat flow rate across the joint ($\pm 2\,\%$) and in the measured T_j (from $\pm 0.8\,\%$ to $\pm 13.4\,\%$). The relative uncertainty in the calculated resistance was determined to be from $\pm 2.2\,\%$ (the thickest specimen and the lowest contact pressure) to $\pm 13.6\,\%$ (the thinnest specimen and the highest contact pressure).

BULK RESISTANCE METHOD RESULTS

Grafoil GTA thermal interface material was selected as the representative graphite-based material. Grafoil GTA has excellent thermal properties typical of other graphite materials as well as flexibility, conformability and elasticity, necessary for interface compliance. These graphite products can be produced over a broad density range ($0.1 - 2.0\,g/cm^3$), where relatively high porosity results in a low contact resistance. By modifying the density and porosity, different material thermal properties can be obtained.

The material was tested as a single, two-sheet and three-sheet stack, providing a wide range of material thicknesses. By measuring the sheet final thickness, it was concluded that the GTA sheets deformed permanently. The difference between the initial thickness t_{m_o} and final thickness t_{m_f} are reported to be from 4.32% to 16.45% (Table 1). The measured surface characteristics are presented in Table 1. Smaller roughness values of GTA 005 sheets were observed while the waviness of all Grafoil GTA materials ranged from $10.30\,\mu m$ to $19.35\,\mu m$.

Experimental Data

The experimental data are plotted in Figs. 2-4 Beside the tests in vacuum, one test for each thickness was conducted in air in order to examine the influence of gap conductance on Bulk Resistance Method. From the data trend at higher pressures it was concluded that the thickness of all tested sheets decreased linearly with the applied load and the bulk resistance region was recognized at pressures above $2\,MPa$.

A very small difference between the loading and unloading thermal resistance data is observable, which leads to the conclusion that the contacting asperities experienced elastic deformation. The negligible resistance difference in the bulk resistance region ($P > 2\,MPa$) is due to the material's permanent deformation. In the contact resistance region ($P < 2\,MPa$) the thermal resistance in the unloading cycle is equal to or higher than the loading cycle thermal resistance. As opposed to the very smooth and flat surfaces of the heat flux meters, the TIM surfaces are wavy, as observed, causing unpredictable contact resistance and small differences between the loading and unloading cycle in the low pressure region. The BRM will be applied to the bulk resistance region where contact resistance can be modeled since material waviness at higher pressures is greatly reduced. The tabulated experimetal data and the more detailed analysis of the

Table 1: Surface Characteristics of Grafoil GTA Specimens

Specimen	No. of Sheets	t_{m_o} mm	σ_m μm	m_m rad	Waviness μm
1 GTA 005	1	0.14	1.35	0.055	19.35
2 GTA 005	2	0.27	1.44	0.070	10.75
3 GTA 005	3	0.42	1.41	0.062	12.18
GTA 005 air	1	0.14	1.26	0.052	14.68
1 GTA 015	1	0.40	1.84	0.072	11.60
2 GTA 015	2	0.78	1.89	0.070	16.73
3 GTA 015	3	1.17	1.81	0.070	12.53
GTA 15 air	1	0.39	1.56	0.062	11.13
1 GTA 030	1	0.80	1.66	0.062	11.70
2 GTA 030	2	1.55	1.68	0.063	10.85
3 GTA 030	3	2.39	1.71	0.059	11.86
GTA 030 air	1	0.78	1.81	0.061	13.30
GTA 5+15+30	3	1.32	1.50	0.056	13.93
			1.61	0.064	11.73
			1.73	0.060	11.50

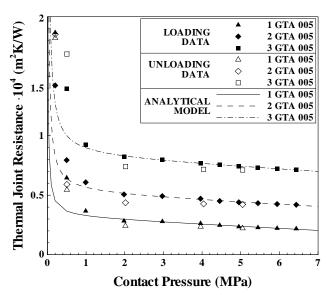Figure 2:   GTA 005 Experimental Data in Vacuum and Model Predictions

Figure 3:   GTA 015 Experimental Data in Vacuum and Model Predictions

data and expeimental investigation is provided by Savija [2].

In Fig. 5, an improvement of thermal joint conductance in the contact resistance region is observed for all tests conducted in air, while in the bulk region performance of the material was slightly reduced due to the trapped air in the gaps which reduced the contact area of the fully conforming surfaces. This increase in the thermal resistance is deemed negligible and BRM developed for vacuum conditions would be even applicable to data obtained in air. Generally, in order to use BRM wh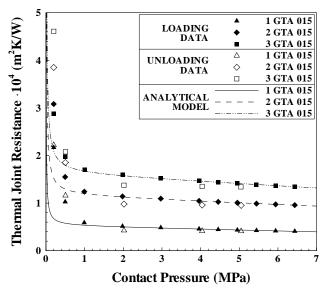en the gaps are occupied with gas or other fluidic substance, the gap resistance term should be determined by using one of many available models in the open literature and incorporated in the joint resistance network and BRM.

Effective Thermophysical Properties of TIM

For all 10 specimens tested in vacuum, the thermal conductivity and effective Young's modulus were determined using both Bulk Resistance Methods. Although the bulk resistance region appears at pressures greater than $2\,MPa$, the last six data points in the
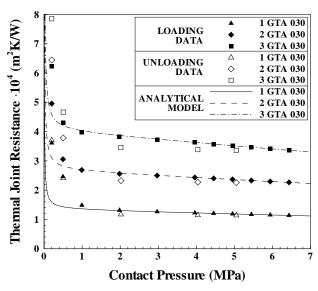
Figure 4:   GTA 030 Experimental Data
in Vacuum and Model Predictions

Figure 5:   Grafoil GTA Data in Air and Vacuum

pressure range from $4\,MPa$ to $6.5\,MPa$ were used to obtain more accurate results. Table 2 shows that the results of the Simple BRM are slightly lower than the results of the General BRM as it was implied in the first part of this study. The Simple BRM underestimates the values of k_m and E_m for approximatelly $3\,\%$ and $6.5\,\%$, respectively. Once the effective modulus is known, the thickness of the material as a function of pressure can be determined. It should be noted that the Poisson's ratio for Grafoil GTA materials was not reported by the manufacturers and for the General BRM calculations a value of 0.3 was assumed as the commonly used approximate value. The Poisson's ratio and Young's modulus of the aluminum heat flux meters are 0.33 and $73\,MPa$, respectively.

Table 2 shows that Grafoil GTA thermophysical properties depend on the sheet thickness. Significant variation is present in the results associated with the thinnest Grafoil sheet GTA 005. For the sheets of the same thickness tested as single or stacked sheets, some differences in k_m and E_m are also observed due to the non-homogeneity of the tested interface material, and experimental error. The uncertainty of the calculated conductivity values range from $\pm 1.1\,\%$ for the three-sheet stack of GTA 030 to $\pm 10.1\,\%$ for a single sheet of GTA 005, whereas the uncertainties in the calculated E_m values range from $\pm 1.2\,\%$ for the thickest specimen, a three-sheet stack of GTA 030, to $\pm 14.4\,\%$ for the thinnest GTA 005 sample. The uncertainty in the BRM results, especially in the E_m, is significantly affected by the error of the thermal resistance-pressure slope used in the BRM calculations, which is higher for the GTA 005 specimens due to the significant non-linearity in the bulk resistance region. The calculated
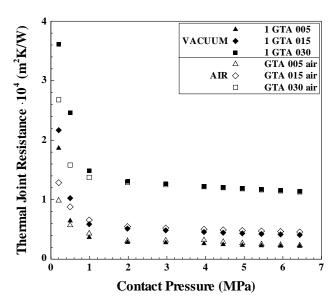
E_m values for the stacked sheets are generally higher than the single sheet results. This holds for all tested specimens, however, the increase is smaller for thicker sheets.

For industrial applications, it is convenient to have an average thermal conductivity simply calculated using the mean average: $4.92\,W/mK$ for GTA 005, $7.25\,W/mK$ for GTA 015, $5.92\,W/mK$ for GTA 030. Also the averaging procedure (Fig. 6) that was already described can be used. The averaged conductivity values are shown in Table 3.

The averaging procedure is very sensitive to the calculated slope used in averaging and the uncertainties of the BRM itself. Therefore, the obtained average material conductivity is not necessarily in the range of the individual conductivity values of the considered tested sheets as it was observed for GTA 005. The averaged thermal conductivity values are consistent for the bulk resistance region pressures, hence a single pressure data set is sufficient to the average material conductivity. By plotting the thermal bulk resistances of GTA 005, GTA 015 and GTA 030 sheets versus *in situ* thickness on the single plot, the average conductivity of $6.2\,W/mK$ for all tested Grafoil GTA materials was calculated. The obtained Grafoil GTA average values are very close to the thermal conductivity of the GTA 005 + GTA 015 + GTA 030 stack, determined with BRM. Testing sheets of all thicknesses in a single stack can be another way of determining the average material thermal conductivity.

The results of this averaging procedure are compared with the conductivity values obtained with ASTM procedure that was already described by Savija et al. [1]. From Table 3 it can be concluded that the

Table 2: Grafoil GTA Thermal Conductivity and Effective Young's Modulus

Specimen	General BRM		Simple BRM		Final Thickness, t_{m_f}		
	k_m W/mK	E_m MPa	k_m W/mK	E_m MPa	Measured mm	Predicted mm	Diff. $\%$
1 GTA 005	4.36	19.11	4.18	18.51	0.13	0.11	-13.07
2 GTA 005	5.29	30.44	5.00	27.55	0.25	0.23	-6.45
3 GTA 005	5.10	44.06	4.84	37.92	0.37	0.37	0.55
1 GTA 015	7.62	28.37	7.41	27.10	0.34	0.32	-5.03
2 GTA 015	6.81	35.85	6.60	33.42	0.67	0.65	-1.95
3 GTA 015	7.31	36.82	7.10	34.42	0.98	0.99	0.92
1 GTA 030	5.95	40.95	5.85	38.94	0.69	0.69	-0.72
2 GTA 030	5.83	41.18	5.73	39.37	1.38	1.33	-3.56
3 GTA 030	5.98	38.84	5.90	37.44	2.05	2.04	-0.24
GTA 5+15+30	6.21	43.40	6.05	40.12	1.17	1.14	-2.48

Table 3: Average Conductivity k_m (W/mK) and ASTM Results for Tested Materials

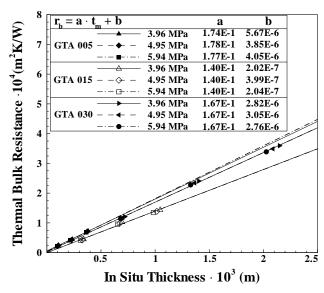| Nominal Pressure MPa	GTA 005		GTA 015		GTA 030		GTA 005,015,030	
	BRM	ASTM	BRM	ASTM	BRM	ASTM	BRM	ASTM
4	5.77	5.47	7.15	7.70	5.99	6.64	6.17	6.68
5	5.63	5.46	7.16	7.94	6.00	6.86	6.18	6.74
6	5.64	5.55	7.16	8.20	5.99	7.08	6.24	6.89

Figure 6:   Bulk Resistance Fits Used
for Thermal Conductivity Averaging

average values obtained with BRM averaging procedure are lower than the values determined using ASTM test procedures, as expected. A consistency of the averaged values with pressure is observed, whereas the ASTM conductivity values increase with pressure.

The above calculated thermophysical properties (Table 2) are introduced in the elastic thermal joint resistance models (Savija et al. [1]) and the models are compared to the first loading cycle experimental data (Figs. 2-4). For the majority of tested specimens, the models agreed within 1% of experimental data in the bulk resistance region. Because of the wavy surfaces of Grafoil GTA sheets, the measured thermal joint resistance at low pressures is much higher than model predictions. The uncertainties of the predicted thermal joint resistance ranged from $\pm 2.9\%$ for 3 GTA 030 specimen to $\pm 14.1\%$ for 1 GTA 005 specimen.

As already proposed, in order to verify the Bulk Resistance Method results, the specimen final thickness was estimated since a linear trend in the bulk resistance region of the unloading cycle was observed for all tested specimens. From Table 2, the maximum difference between the measured and predicted final thickness is observed for the GTA 005 single sheets. The uncertainties associated with the final thickness prediction range from $\pm 2.6\%$ for 3 GTA 030 specimen to $\pm 16.8\%$ for 1 GTA 005 specimen. Since the measured and predicted final thickness difference Δt_{m_f} (Table 2) is smaller then the overall uncertainty of the final thickness values, the results of the Bulk Resistance Method are found to be satisfactory. The more detailed

discussion on BRM results and uncertainty analysis is provided by Savija [2].

SUMMARY AND CONCLUSIONS

The thermal performance of a thermal interface material (TIM) can only be properly assessed if the thermal resistance data for a wide pressure range are known. In addition to the thermal resistance data, complete information on the experimental parameters and procedures is necessary to draw a conclusion about material performance.

Thermal resistance data are obtained for Grafoil GTA material tested as single and stacked sheets and k_m and E_m are determined applying BRM. A significant difference in the calculated properties between Grafoil GTA sheets of different thickness was observed. The results of the proposed method, especially E_m are very sensitive to the obtained slope in the bulk resistance region. In order to obtain the average thermal conductivity of the material, the mean average calculation and proposed averaging procedure were used.

The experimental data and the model for conforming surfaces, which included the BRM results, agreed very well in the bulk resistance region, whereas considerable discrepancy appeared at low contact pressures. The analytical model can be used as a lower bound for the thermal joint resistance in the contact resistance region of the non-conforming surfaces such as TIM's surfaces.

ACKNOWLEDGMENTS

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