

Thermal Resistance Characterization of a Nano-Graphite Composite Thermal Interface Material

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Abstract

This paper discusses the design challenges for a high-precision in-situ thermal interface material (TIM) tester and will show how the system was optimized to meet these challenges. After validating the testing system, it was then used to test graphite nano-platelet (GNP) composite. The results presented in this paper will provide insightful information for researchers who are interested in designing a high performance thermal interface testing system as well as those who are looking for new, highly conducting TIMs.

I. Introduction

In high power microelectronics packaging, the thermal resistance can be divided into two dominant parts: the thermal resistance from the heat sink to air and the thermal resistance of the interface material, the latter of which could count for more than 50% of the total package thermal resistance. Thermal Interface Material (TIM) plays a key role in thermally connecting various components and enhancing the heat transfer from inside the chip to the outside case. With the continual pressure toward increasingly dissipated power coupled with the reduction on die size and thickness, the demand for an effective cooling solution rises not only in the exploration for effective fans and bulky heat sink solutions, but also in reducing the overall junction to case thermal resistance, R_{jc} . As a rule of thumb, the maximum dissipated power on a chip is

constrained by maximum junction temperature, T_j , which is the maximum heat flux dissipated on a chip, Q_{max} divided by the junction to case thermal resistance, R_{jc} . In typical package architecture, R_{jc} normally includes thermal resistance of a chip, TIM, case and sometime also a TIM2 and heat spreader. Thermal resistance of a 500 μ m-thick silicon chip is about 0.03 $^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$, and the typical thermal resistance of TIM ranging from 0.05 – 0.25 $^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$ or more depending on the thickness and the applied pressure. Thus we know that the thermal resistance of TIM is an order of magnitude higher as of R_{si} and it is the dominant factor of total R_{jc} , normally accounts for over 50% of R_{jc} . Figure 1 also shows the historical review of the best-in-class TIMs.^[1]

Since 1990's innovative thermal interface materials have been an active research area. There are two main

approaches: nano-structured materials, such as carbon nanotubes^[2,3] or nano-graphite composites^[4,5]; and metallic materials.^[6] Xu et al.^[7] from State University of New York, Buffalo reported that a 0.6 vol.% single-walled carbon nanotubes in a poly (ethylene glycol) based dispersion was as effective as solder in enhancing thermal contacts, with an effective thermal resistance of $0.05\text{ }^{\circ}\text{C-cm}^2/\text{W}$. They also claimed that an excessive amount of nanotubes (e.g. 1.8 vol%) degraded the performance because of conformability loss. Their findings showed that the nanotubes were more effective than hexagonal boron nitride particles but were less effective than carbon black, which gave an effective thermal resistance of $0.03\text{ }^{\circ}\text{C-cm}^2/\text{W}$. Tim Fisher's group in Purdue^[8] recently reported a metal foil with dense, vertically oriented carbon nanotubes (CNT) arrays with an effective thermal conductivity of 80 W/mK , or an effective thermal resistance of $0.04\text{ }^{\circ}\text{C-cm}^2/\text{W}$ at moderate pressure. Their report showed that coating a metal foil had 50% reduction of the overall

thermal resistance. IBM reported TIM thermal resistance below $0.02\text{ }^{\circ}\text{C-cm}^2/\text{W}$ with combination of highly filled material and ultra low bonding line using hierarchical nested channel.^[9] Majumdar's group in Berkeley^[10] reported their CNT grown by thermal CVD can achieve a cross-plane thermal conductivity $\sim 250\text{ W/mK}$, when the tip is welded with a thin-layer of Tin. Its thermal resistance can achieve $0.01\text{ }^{\circ}\text{C-cm}^2/\text{W}$. Thus far, these are the best values reported in the literature. However, because there is no standard TIM testing method, the data was obtained from an in-house lab measurement system. This must be taken into consideration when making comparisons of the absolute values. Additional consideration must be given for the bond line thickness, measurement setup and testing conditions, etc.

Developing an accurate testing technique to benchmark these innovative TIMs is very challenging because measuring R_{th} down to $0.01\text{ }^{\circ}\text{C/W}$ is beyond the capability of commercially available testers.^[11]

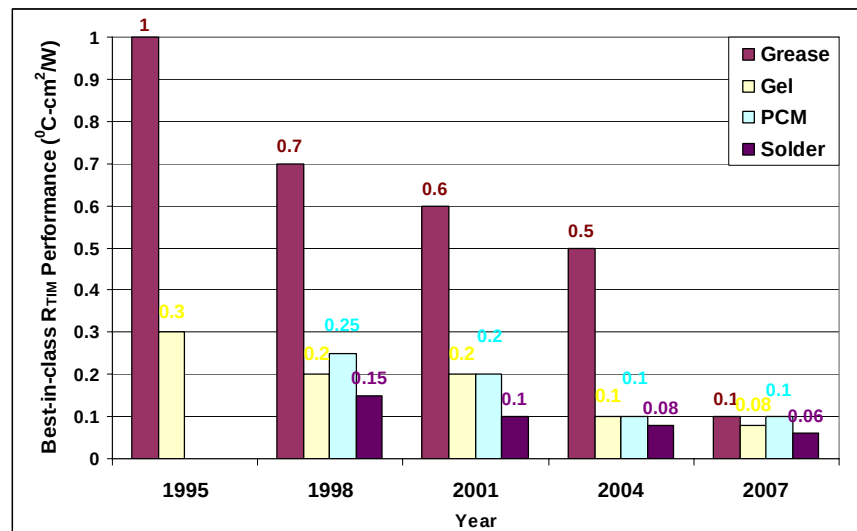


Figure 1 Historical review of Best-in-Class thermal performance of different type of TIMs' (Unit, $^{\circ}\text{C-cm}^2/\text{W}$)

II. ASTM D5470 standard for TIM testing and its limitations

Currently, ASTM D5470 standard for TIM testing has been adopted by many TIM

vendors. Figure 2 illustrates a schematic of ASTM D5470 standard tester.^[12] Basically, it consists of two parts, the top part is the heater block, which creates the temperature

difference and the bottom part is a cold plate to keep the temperature stabilized. The temperature difference, ΔT , across the sample is measured by the thermocouples nearby the sample and the heat flux, Q , is derived by the temperature readings of thermocouples at different locations. The thermal resistance values of the DUT are then calculated by, $R_{th} = \Delta T / Q$. Several commercial TIM testers are available on the market which are compliant with this standard^[13,14].

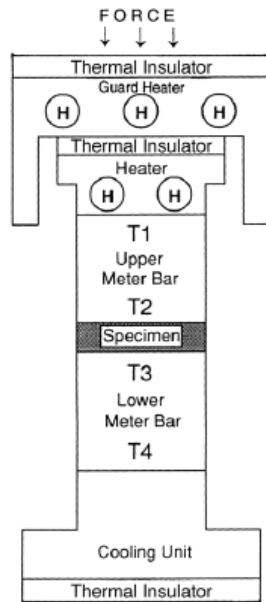


Figure 2 A schematic of ASTM D5470 standard tester

However, this type of measurement has its resolution limits. The heat flux calculated from the differential thermocouple readings is not reliable. In most cases, the accuracy of temperature readings from thermocouples is limited to 0.1°C . In addition, the meter bars used in the testing do not reflect the issues of surface wetting and contact resistance between the TIM and the chip in the real application.

III. Design an application-specific TIM tester and measurements validation

Our proprietary TIM tester is an application specific-type tester which consists of four major parts:

1. A thermal test die ($16 \times 16 \text{mm}^2$) with embedded heater and diode and flip-chip bonded on a test board. The embedded heater can provide 1 W/mm^2 heat flux and a total power of 256 W. The diode sensor has a temperature reading accuracy of 0.01°C ; the heater provides the heating power to create the temperature difference and the diode are used to measure the temperature change at each measurement.

2. A cold plate with embedded micro-channels, which provides a cooling power density up to 1000 W/cm^2 . This provides a high stability of the cold-side temperature.

3. A vacuum sample holder together with a pressure-controlled clamping module

4. High precision in-situ thickness measurement system with repeatability down to $0.05 \mu\text{m}$. The TIM is sandwiched between the back-side of the thermal test die and copper cold plate. The heat is dissipated from the silicon, propagates through TIM and into the cold plate. Figure 3 shows a snapshot of our TIM tester as well as the control software.

When compared with the ASTM D5470 standard tester, our tester has the following advantages: it reflects the real application scenario, it has better temperature resolution, and metal expansion at high temperature levels is not an issue. Furthermore, with the embedded thermal test die, it is possible to use the transient testing method proposed by Renz etc.^[15] to conduct tests instead of steady state measurements, which saves testing time and improves accuracy. This is worthy of exploring in near future.

To validate the testing system, we first tested Sil-pad 2000 thermal pads of different thickness, which were obtained from Bergerquist. Figure 4 plots the measured thermal resistance versus the thermal pad thickness and the data is illustrated on a

linear curve. It shows good correlation between our measured results and the data reported by the manufacturer.

There are many factors affecting the TIM testing, especially the grease-type of the material, e.g. spacer size, uniform thickness and applied pressure. To make a fair comparison, standardized parameters were necessary. Figure 5 illustrates the impact of applied pressure on thermal resistance values. From the measurements, we can see when the pressure is over 100 psi, the thermal resistance change versus the applied pressure is less sensitive than at the lower pressure levels. Thus in all our

measurements, we fixed the applied pressure at 110 psi. **Figure 6** shows the temperature distribution of the thermal test die with different spacer sizes. From the chart, we can see that there is a large non-uniformity temperature distribution when the spacer is on all four sides and is 2mm-wide. When we reduce the spacer width and place it on only two sides, the temperature distribution of the active region is more even. Non-uniform temperature distribution on the die will affect the accuracy of calculating thermal conductivity using 1D conduction formula.

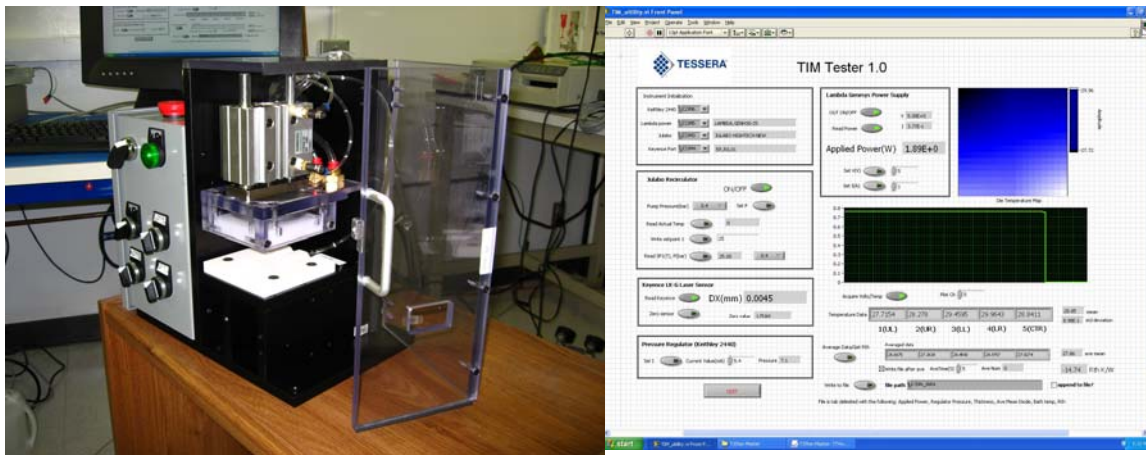


Figure 3 A snapshot of our proprietary TIM tester system and the control software interface.

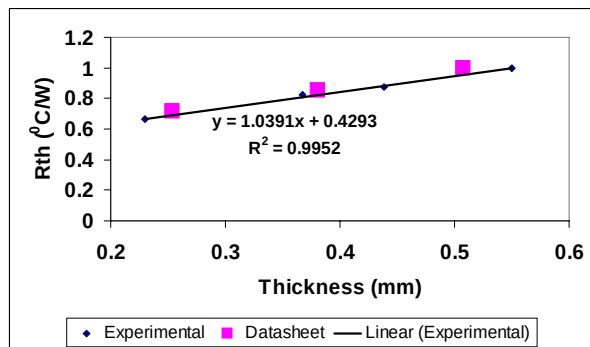


Figure 4: Measurements validation: Sil-pad 2000 thermal pads from Bergerquist thermal resistance versus sample thickness. (Data obtained at 100 psi and 20W heating power.)

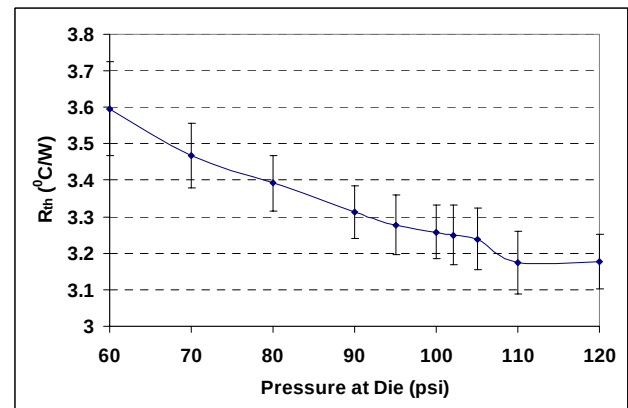


Figure 5 The thermal resistance value of silicon grease changes with the applied pressure.

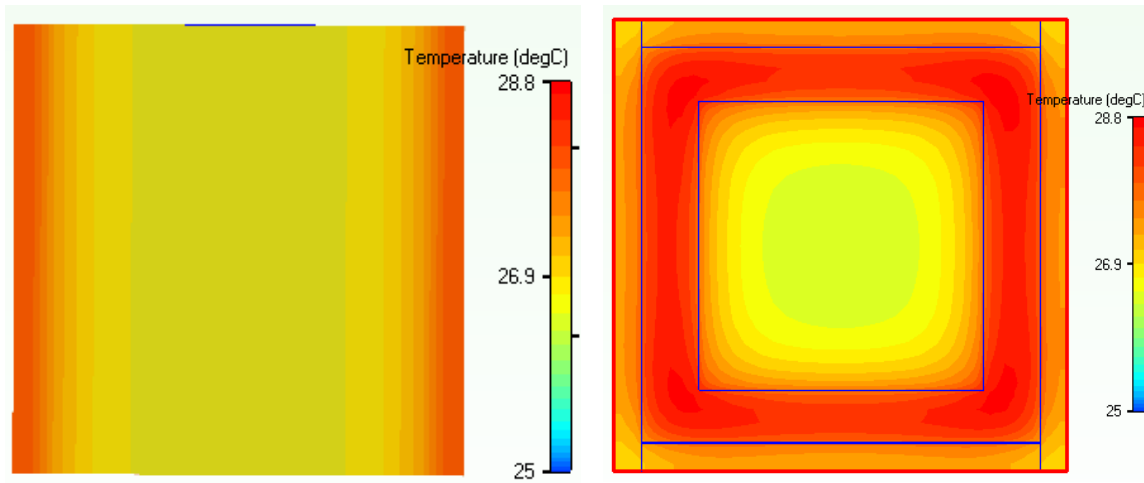


Figure 6 Flotherm simulated results of the temperature distribution with 1mm spacer (left) on two sides and 2mm spacer on all four sides (right).

IV. Measurements of GNP-based TIM

After validating the system, we began testing some graphite nanoplatelet (GNP)-filled epoxy TIMs. Figure 7 is an example of the samples we measured, and shows the GNP-filled epoxy TIM. GNPs comprised of 2 to 8 graphene layers are prepared by intercalation and exfoliation of graphite. High shear mixing and sonication of exfoliated graphite in acetone yields dispersion of GNPs.⁴ Epoxy resin was added to acetone dispersion of GNPs and further sonicated, sheer mixed and the acetone was evaporated to obtain composite material of particular composition (*ca.* 20 wt%).

Figure 7 shows the measured thermal resistance values versus the sample thickness. The thickness is in-situ measured

by the laser sensor. We can see that the thermal resistance of this sample matched well with the linear curve having a less than 2% deviation. Thus we can derive the thermal conductivity from the slope of the curve and obtain the contact resistance from the intercept of the line. The calculated thermal conductivity for this material is about 2.2 W/mK. Comparing to pure epoxy, the thermal conductivity of GNP-filled epoxy is over 10 times better. The contact resistance is about 0.24 K/W, relatively higher than conventional grease-type material. This is because the supporting matrix, epoxy, has not been optimized for the surface wetting.

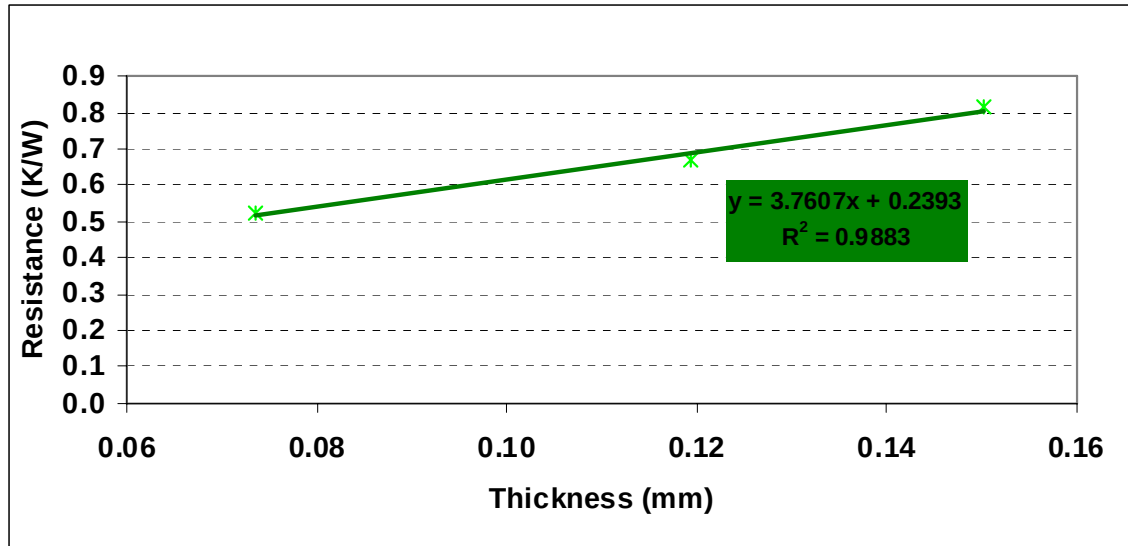


Figure 7 Measured GNP-filled epoxy thermal grease thermal resistance versus sample thickness

V. Conclusions

This paper proposed a new application specific thermal resistance testing system, which can achieve better resolution than the conventional ASTM D5470 standard tester. Additionally, it presented results of the impact of the spacer size and applied pressure on TIM thermal resistance measurements. Findings show that parameters must be fixed in order to obtain meaningful comparison among different types of TIMs. GNP-filled materials are very promising in making highly thermally conducting TIMs. However, finding the right supporting matrix, which can wet the silicon and copper surface to reduce the contact resistance, is very important. Furthermore, because of the anisotropic properties of GNP, a method to orientate them in a such a way as to improve the cross-plane thermal conductivity needed in TIM application is also worthy of further research.

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