Understanding Criticality of Thermal Performance in Thermal Interface Material Applications

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Abstract
Thermal interface material (TIM) is used in between a heat generating component (e.g., microelectronic packaging) and a heat spreading component (e.g., heatsink or cooling plate) to create an effective path for the heat (Phonon) to travel. Standard heatsink and heat generating component surfaces are generally uneven and rough. Actual metal to metal contact is no more than 10%. These surface imperfections allow air to get trapped in between the two surfaces. Air, being a thermal insulator, prevents the heat from dissipating and thus the device/system fails to maintain the required operating temperature to meet the reliability and functionality needed. Replacing the air with the “right” thermal interface material is the focus of this research.

TIM is a composite of thermally conductive fillers dispersed in a polymer matrix. A higher filler loading causes a higher bulk conductivity. Common practice among design engineers is to utilize output from thermal modelling & simulation to specify a TIM with a certain thermal conductivity to meet the system’s thermal needs. What many engineers miss is the impact of thermal boundary resistance that could have significant effect on the overall thermal management of the design. This paper discusses how to characterize thermal performance of TIM beyond the bulk thermal conductivity. Boundary/interfacial thermal resistance and impedance will be explored as a function of TIM wetting ability, bond line thickness and surface conditions. This paper will discuss the importance of thermal conductivity, thermal resistance/impedance in a real application scenario.

Key words
Thermal Interface Material-TIM, Thermal Conductivity, Contact Resistance, Thermal Impedance, Bond Line Thickness (BLT), Heat generating component, Heatsink.

I. Introduction
Power electronics are integral parts of power components, power supplies, 5G network, automotive and defense/space applications. All modern power electronics have two critical factors in common that drives the need for unprecedented thermal management: first, increased transistor density to meet the higher demand in increased computing power and second, component miniaturization leading to higher heat flux. It is well known in the electronics reliability field that 55% of the component failure in electronic devices is related to excess heat. The Arrhenius equation as in (1) [1] predicts for electronics, the lift of the device decreases by half [2] by increasing the device temperature by 10°C. Design engineers mitigate this issue by carefully selecting Thermal Interface Materials (TIM) to keep the system/device temperature at the desired level.

\[
AF = \frac{t_{\text{use}}}{t_{\text{test}}} = \exp \left[ \frac{E_A}{k} \left( \frac{1}{T_{\text{use}}} - \frac{1}{T_{\text{test}}} \right) \right] \tag{1}
\]

AF - Acceleration Factor
T - Temperature
\(E_A\) - Activation Energy
k - Boltzmann Constant

The primary function of TIM is to replace the air in between the heat generating component and the heat spreader/heatsink to improve heat dissipation. Figure 1 shows an illustration of a typical microelectronics packaging assembly with heatsink and TIM. Unevenness and roughness
of the surface must be taken into consideration when implementing a thermal solution.

For the heat to be adequately dissipated, it must reach the heatsink surface first. Efficiency of heat transfer from the hot device to the cold heatsink depends on effective thermal resistance of the bulk TIM and contact resistance at both surfaces.

II. Definitions

Thermal Conductivity

Thermal Conductivity (TC), designated as $k$, is the bulk property of a material that indicates its ability to conduct heat. It does not depend on the geometry or interfacial conditions of the test set up. Fourier’s law of thermal conduction provides us a way to calculate $k$ using the equation as in (2).

$$ Q = -kA \frac{dT}{d} $$  \hspace{1cm} (2)

- $Q$ - Heat flux (W)
- $k$ - Thermal conductivity (W/m-K)
- $A$ - Area (m²)
- $d$ - Thickness (m)

Figure 2 is the graphical representation of Fourier’s equation.

Thermal Resistance

Thermal Resistance (TR) can be thought of as the opposite of thermal conductance. For a steady state conduction as shown in Figure 2, the Fourier’s equation for thermal resistance can be written as (4).

$$ R = \frac{d}{kA} $$  \hspace{1cm} (4)

- $R$ - Thermal resistance, °C/W

Thermal Impedance

Thermal Impedance (TI) is similar to thermal resistance and often used interchangeably. However, there is a distinct difference between thermal resistance and impedance. TI is defined as the temperature gradient per unit of heat flux, passing through the interface. As shown in (5), TI is obtained by simply multiplying the resistance, $R$, by the area over which the heat is dissipated.

$$ Z = RA $$  \hspace{1cm} (5)

TI includes bulk thermal resistance of the TIM and contact resistance between TIM and the two surfaces in contact with the TIM. As the thermal resistance is directly proportional (3) to the thickness of the TIM, the thinner the TIM thickness, the lower the thermal resistance. Contact resistance on the other hand depends on the two contacting surface conditions and the ability of the TIM to fill in the surface roughness (Figure 1). Surface roughness and unevenness can trap air (air is a thermal insulator) reducing the effectiveness of TIM to transfer heat. Figure 3 is a graphical representation of the resistance in series across the component and heatsink assembly. Total resistance is the sum of all three resistances (impedance).

$$ Z_0 = R_1 + R_0 + R_2 $$
III. Thermal Performance Characterization

Thermal performance characterization of TIM is critical in selecting the right TIM for your application. However, characterization can be challenging as there are many industry standards in use. Examples of such standards are ASTM D5470, JESD51:1-14, Semi Std 750, and Semi Standards G68-96, just to name a few. In addition, these standards could have many test methods/variations. It is imperative to use a standardized test method to enable the end user to compare TIM products from different suppliers.

There are two common types of testing done at the material level (TIM characterization). They are Steady State and Transient testing. The most common steady state testing equipment are based on ASTM D5470 standard and Transient testing is based on ASTM E1461 Laser Flash method. This study used ASTM D5470 test method to characterize all TIMs in testing.

Steady State Thermal Testing—ASTM D5470-6 [3]

Typical ASTM D5470 test set up to obtain Effective Thermal Conductivity is shown in Figure 4. Thermocouples (TC) are imbedded on the surface of the hot and cold bar to measure the exact temperature of both surfaces. This set up assumes the following once steady state is reached:

- Temperature gradient is uniform across the column
- All power applied goes through the column only
- Heat flow is 1 dimensional
- No interfacial resistance (negligible amount) between the cold and hot bars
- Both surfaces are flat and level

When the sample is placed between the two bars, it poses some resistance to the flow of heat. Based on the measured temperatures and known thickness a TI can be calculated.

IV. Experimental Study

As described in section II, thermal performance of a TIM depends on the thermal conductivity, TIM thickness, area, and contact resistance at both interfaces. Contact resistance on the other hand depends on the TIM’s ability to wet out (fill in the microscopic surface imperfection that could trap air) the mating surfaces. Better wet-out can be achieved by various means. Examples are, smoother surfaces, TIMs wetting ability (liquid vs. pad), and increased pressure for better contact. This experimental study explored the effects of types of TIM (Pad vs Gel), TIM thickness and contact pressure as phase 1 of this study.

Experimental Set-Up

First part of the above hypothesis was tested by conducting a 2K DOE (Design of Experiment) as shown in Table 1. A Gap Pad and Gel were selected for this study with listed Thermal Conductivity of ~ 5 W/m-K. The second part of the study (Ladder Study) used various pad thicknesses and assembly (test) pressure to observe its effect on Thermal Impedance. The sample used for this study was an ultra low modulus Gap Pad with TC of ~ 6 W/m-K. Table 2 shows the experimental matrix.

Table 1. 2K DOE Table

<table>
<thead>
<tr>
<th>TIM Type</th>
<th>TIM Thickness, (mm)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gel</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>3</td>
</tr>
<tr>
<td>Gap Pad</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2. Ladder Study for effect of contact pressure

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Contact Pressure (psi)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>60</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>125</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 4 shows the equipment used is this study. Gap Pad samples were cut to a diameter of 33mm (1.3”). Liquid samples are applied to the tester with a measured volume to achieve desired thickness with a diameter of 33mm as shown in Figure 5. The TIM tester has a built-in thickness.
measurement system that accurately measures and records the thickness of each sample.

![TIM Tester](image)

**Figure 4. Test equipment**

![Test specimen examples](image)

**Figure 5. Test specimen examples**

**Predictions**

As a Gel is a liquid TIM it should provide better wet out of the surfaces leading to lower thermal resistance as compared to a Pad. The same theory should be applicable to thinner TIM thickness as described in section II. By increasing the assembly pressure for a Pad, we should also observe better wet out.

**V. Results & Analysis**

**Thermal Impedance Analysis**

As predicted, DOE analysis for TI shows regardless of product type, TIM thickness has the largest impact on the TI: The thinner the TIM thickness, the lower (better) the TI. Product type analysis also agree with the prediction that Gel (which is a liquid) wets out the interface better leading to lower TI.

Figure 6 shows the main effect plot and ANOVA analysis as obtained from MiniTab analysis. P-Value of 0.0 for all main effects and interaction indicates statistical significance of product type and TIM thickness.

**Effective Thermal Conductivity Analysis**

Effective TC was calculated using (3) with the measured TIM thickness as described in section II. Effective TC depends not only on the bulk TC of the sample but also on the contact resistance. The trends observed in Effective TC is similar to TI as predicted by the hypothesis. The result from the MiniTab analysis is presented in Figure 7.

![Main Effects Plot for TI (Z) Fitted Means](image)

**Figure 6. DOE analysis for Thermal Impedance**

![Main Effects Plot for TC Fitted Means](image)

**Figure 7. DOE analysis for Effective TC**

**Assembly (Test) Pressure Effect**

Assembly pressure effect test was conducted using the same test set-up as shown in Figure 4. A typical sample condition before and after the testing is shown in Figure 8 for 125 mil thick sample. As expected, at higher pressure, the sample becomes much thinner and squeezes out to the outside perimeter of the test fixture.

Figure 9 shows the results from the ladder study as described in Table 2. As predicted, there is a clear trend in improved thermal performance (lower TI) with increased pressure regardless of initial sample thickness. This is the result of better wet out and thinner bond line with increased test pressure.
The primary objective of this study was to provide the end user of Thermal Interface Materials a means to select, evaluate and implement a thermal solution for their applications above and beyond the review of published Technical Data Sheet (TDS). Traditional approach of focus on the TC of a TIM is no longer sufficient to meet today’s stringent requirements of high performing electronics. A better approach is to evaluate the thermal performance of a TIM that takes into account bulk thermal conductivity, TIM’s ability to wet out the contact surfaces and bond line thickness.

Results from this study clearly demonstrate the bond line thickness effect on the overall thermal performance. Figures 6 & 7 show regardless of the TIM type, Pad or Gel, thinner bond line provides lower impedance and higher Effective Thermal Conductivity.

This study further demonstrates by mechanically pushing the air out of the interface, thermal performance can be improved. However, we must consider the practical aspect of this strategy. Most gap pads cannot be compressed more than 40-50% of its original thickness. This is demonstrated in Figure 8 where excess force destroy the sample. This will create high risk in real applications.

Acknowledgment
I would like to express my sincere gratitude to David Franco, Peter Jones, and John Prindl from Henkel for conducting all laboratory tests and provide insight to the test equipment and methods. Without their support, this work would not have been possible.

References

VI. Summary and Conclusion
The primary objective of this study was to provide the end user of Thermal Interface Materials a means to select, evaluate and implement a thermal solution for their applications above and beyond the review of published Technical Data Sheet (TDS). Traditional approach of focus on the TC of a TIM is no longer sufficient to meet today’s stringent requirements of high performing electronics. A better approach is to evaluate the thermal performance of a TIM that takes into account bulk thermal conductivity, TIM’s ability to wet out the contact surfaces and bond line thickness.