Next Generation Phase Change Material for High Power Electronics

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Abstract

The demand to increase speed and performance of electronic devices while keeping the footprint small, has increased the power density of electronic devices beyond what we thought possible merely a decade back. Telecom/Datacom, Industrial, Automotive and Consumer electronics such as gaming console are pushing the package size to be greater than 70mm X 70mm and power density greater than 100W/cm^2. Most electronic devices are running at high power with high frequency power cycles. This elevated power density and high frequency cycling causes the temperature to rise beyond the operating thresholds of the device. To achieve the functionality and reliability of these devices, proper thermal management must be employed.

Research shows, use of Phase Change Material (PCM) in TIM 2 and TIM 1.5 applications is an interesting and effective technique in maintaining the temperature of advanced electronic devices to its desired target. Although PCM has been in the market for decades, the recent advancement in high power electronic is accelerating the development of next generation PCM as a desired solution to maintain electronic devices temperature. In this paper we will discuss some of the new developments in PCM with special focus on power electronics and Telecom/Datacom applications. Methods to characterize PCM and comparison of different PCM will also be discussed.

Key words

Thermal Interface Material-TIM, Phase Change Materials, Thermal Conductivity, Contact Resistance, Thermal Impedance, Bond Line Thickness (BLT)

I. Introduction

Power electronics are integral parts of power components, power supplies, 5G network, automotive, computing devices and much more. 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, increased power density due to component miniaturization. Smoyer and Norris [1] presented historical data showing power density of commercial processors have reached above 100 W/cm^2 as shown in Figure 1a and 1b. Generally higher power densities are detected in certain spots on the die leading local hot spots. Temperatures in these hot spots has the potential to exceed upper temperatures threshold of the component impacting the performance and reliability of the device. It is well known by electronics reliability engineers that 55% of the component failure in electronic devices is related to excess heat. With fast switching frequency devices such as 5G/6G network and power electronics, this risk is specially concerning for safety and reliability of the device. The Arrhenius equation as in (1) predicts for electronics, the life of the device decreases by half [2] by increasing the device temperature by 10^{0}C. One of the most effective ways to address this issue is to reduce thermo-mechanical stresses of these high-power devises by employing various thermal management schemes. Thermal management schemes may include active, passive or a combination of the two methods. Passive thermal management which uses TIM, is probably one of the most cost-effective ways to address this issue. Design engineers are constantly searching for the "right" TIM to meet their thermal design criteria.

$$AF = \frac{time_{use}}{time_{test}} = exp\left[\frac{E_A}{k}\left[\frac{1}{T_{use}} - \frac{1}{T_{test}}\right]\right] \quad (1)$$

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

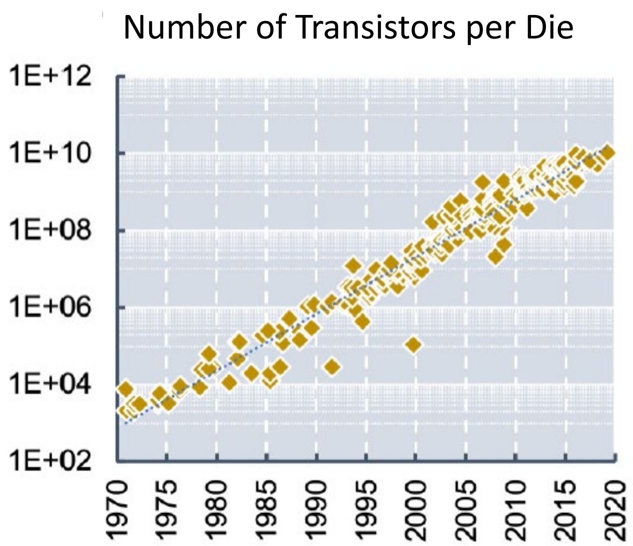

Figure 1a. Historical trend of number of transistors per die [1].

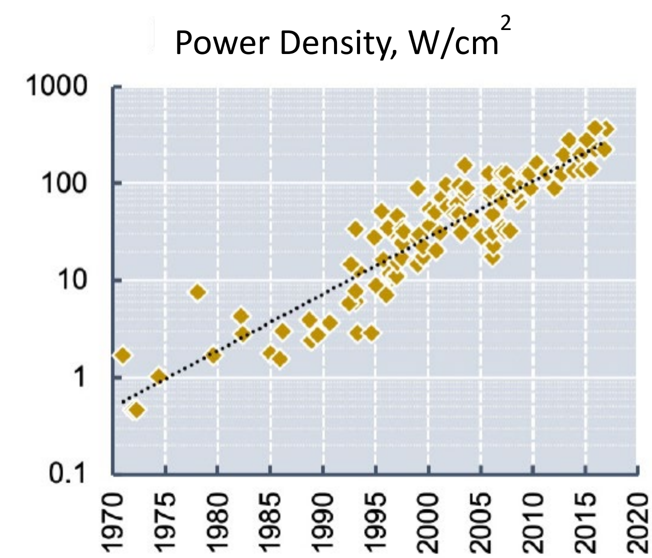

Figure 1b. Historical trend of power density of commercial processors [1].

Figure 2 shows an illustration of a typical microelectronics packaging assembly with heatsink and TIM. In theory, the heat sink should extract the heat from heat generating devices and dissipate it to the environment through conduction heat transfer mechanism. For the heat to be adequately dissipated, it must reach the heatsink surface first through contact between the two surfaces. However, most heat sink design only provides approximately 10% contact between the two surfaces. As Figure 2 illustrates, the unevenness and roughness of the surface entraps air in between the two surfaces causing inefficiency in heat dissipation. Replacing the air by incorporating a TIM solution has proven to be highly effective in enhancing the performance and reliability of the electronics devices.

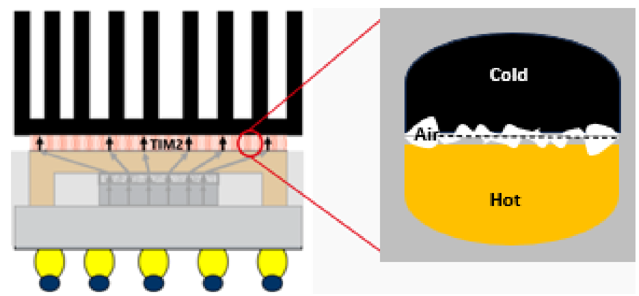

Figure 2. Illustration of rough interfaces

Traditionally, efficiency of heat transfer from the hot device to the cold heatsink depended on effective thermal resistance of the bulk TIM and contact resistance at both surfaces. In addition, high-power electronics will go through high frequency power cycles. Hence, the new, advanced TIM solutions must be capable of managing the transient thermal profiles during power cycles by delaying the thermal response of the device. One such solutions is the use of Phase Change Material (PCM) as a thermal interface material.

II. Phase Change Materials Basics

Phase Change Materials (PCM), as the name implies, goes from a solid phase to a liquid phase and vice versa at specific temperatures. PCM is used both as a thermal storage and thermal conductive applications. When PCM is used in thermal storage applications, latent heat of fusion becomes very important. Phase change occurs when heat is introduced to PCM as seen in Figure 3. Latent heat property couple with the high capacitance of these type of PCM delays the temperature rise of the device/system, extending system life. Figure 3 shows typical behavior of heat absorbing/storing PCM in use [3].

For thermal conductive applications, which is the most common type of PCM used as TIM, latent heat is not a key consideration. As heat is introduced to the device, the material will begin to melt reducing bond line thickness and contact resistance. Figure 4 illustrates various stages of the PCM in action. The efficiency and reliability of PCM comes due to complete wet out of the interfaces and improved pumpout resistance.

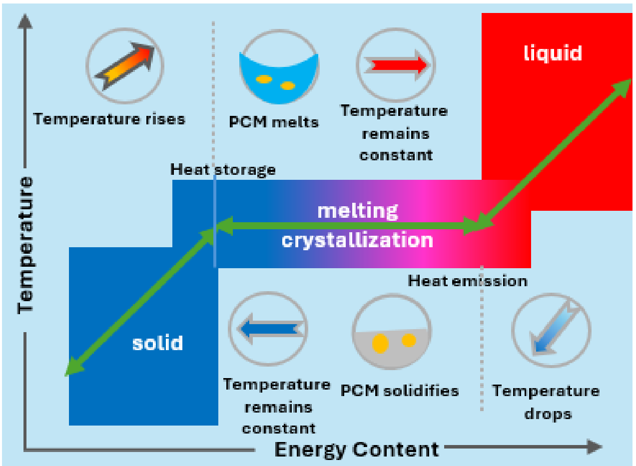

Figure 3. Illustration of heat storing PCM behavior with power on and off cycle.

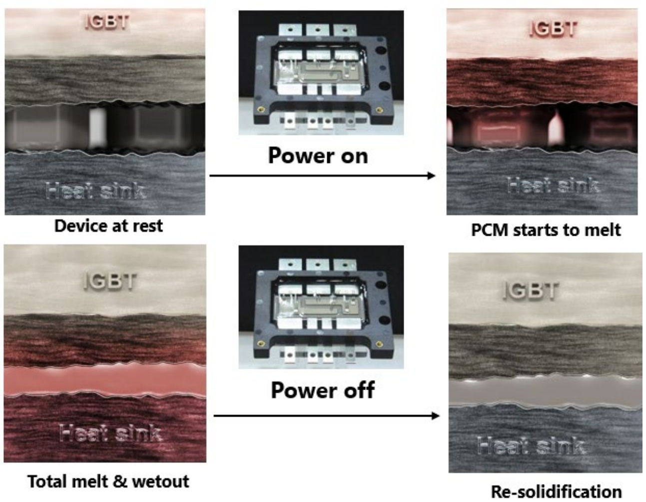

Figure 4. Illustration of heat transferring PCM behavior with power on and off cycle

Most commonly used PCM in electronics thermal management are low temperature thermoplastics that combine the wetting properties of a grease with the convenience of being a solid at room temperature. Examples of PCMs are paraffin waxes and hydrocarbons with inorganic and metallic fillers to enhance thermal conductivity. These PCM materials melt in the range of 40°C to 65°C, providing wide range of design options for material developers. In addition, these materials are chemically inert and show no corrosion. Based on the design, it can have a sharp melting point (Paraffin wax) or a range (Thermoplastic) over which it starts to soften or melt. Figure 5 illustrates this behavior.

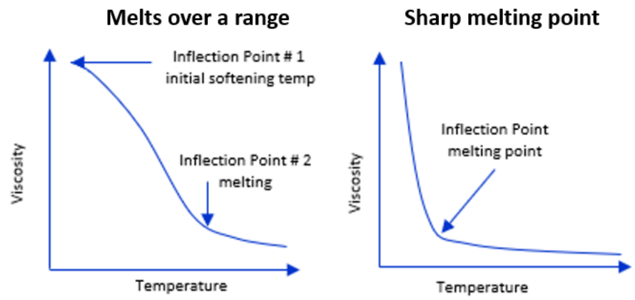

Figure 5. Illustration of PCM behavior with increased in temperature.

Phase change materials have been in use for electronics cooling for over 20 years. Traditional PCM was adequate to address the thermal management needs of low to medium power chips as a grease alternative. Thermal grease has been the golden standard TIM for thin gap applications with high thermal management demand due its efficiency in transferring heat. One of the challenges with grease is its lack of long-term reliability due to a phenomenon knows as pump out. PCM shows improvement over grease regarding pump out, hence reliability, but still lack in efficiency as compared to grease. One primary source of inefficiency of PCM comes from the fact that it needs high pressure to completely wet out the interface and reach minimum bond line similar to a grease, which need little to no pressure. This high pressure requirement of older generation of PCM limits it use as it can damage the sensitive components.

High power and high frequency devices, demand a new class of PCM with higher thermal conductivity, lower interfacial resistance, low pressure assembly and lower/no pump out. PCM TIM suppliers look in to 4 major areas when designing advanced PCM for power electronics. Figure 6 shows these 4 areas with key considerations for each area.

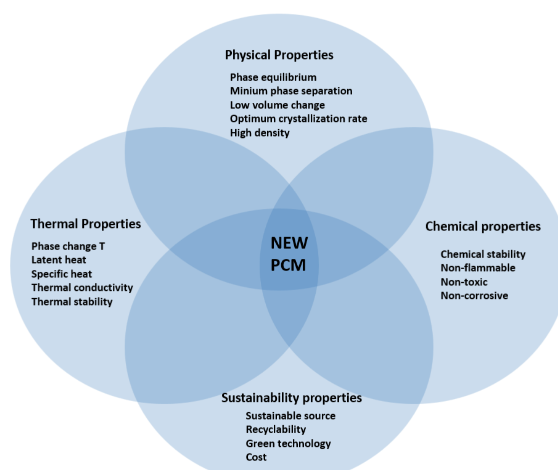

Figure 6. Design considerations for advanced PCM.

In the following sections we will discuss methods to characterize high performing PCM, with special consideration of test equipment effects. We will use one of new PCM developed by Bergquist brand Henkel PCM material as a case study and compare it against commercially available comparative products.

III. Thermal Performance Characterization

Thermal performance characterization of TIM is critical in selecting the right TIM for your application, especially when it comes to thin bond line applications. Test methods that work well for other TIM, such as Gap Pad, Gap Filler, Thermal Gel etc. is not adequate when it comes to PCM and Grease. Characterization can be challenging as there are many industry standards in use and many equipment in use for same test standard. Examples of such standards are ASTM D5470, JESD51:1-14, Semi Std 750, and Semi Standards G68-96, just to name a few and equipment examples are TIM 1300 & 1400 from Analysis Tech, TIM tester from LonGwin, TIMA 5 from NanoTest and TIM tester from ZFW Stuttgart.

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 compare the impact of different test equipment and materials.

Steady State Thermal Testing-ASTM D5470-6 [4]

Typical ASTM D5470 test set up to obtain an Apparent Thermal Conductivity and Thermal Impedance (TI) which are shown in Figure 7. 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
- Testing temperature is 50˚C

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. Effective Thermal Conductivity can be calculated from measured Thermal Impedance and measured sample thickness (in general 3 different thicknesses). As mentioned earlier, this method works well for thicker TIM characterization. When it comes to PCM, where thickness can be as low as 25 microns, some of the standard equipment show deficiency. High resolution Thermal Tester with high precision is critical to accurately capture the performance of advanced PCMs.

IV. Material Description

This study used Berquist Hi Flow THF 5000UT PCM film and a commercially available similar PCM as a case study to demonstrate the impact of TIM tester on the thermal performance of PCM.

Berquist Hi Flow THF 5000UT

THF 5000UT is the new generation of PCM offering from Henkel, design to address thermal management needs for Next Gen data center (Switches, Routers, Servers etc.), industrial power electronics and high-end consumer electronics (Memory, SOC, CPU, GPU, etc.). This product is designed to work with low pressure assembly (≤20 psi) for sensitivity, large components which can be damaged by high assembly pressure. The base chemistry is high temperature stable hydrocarbon phase changing resins with high performing ceramic fillers. Even though it can be offered as a paste or film, the case study here uses film format for ease of comparison. Table 1. shows the basic properties of the two materials used in this study.

Table 1. Test material characteristics (Data from TDS).

Characteristics	THF 5000UT	Product X
Product form	Pad	Pad
Thermal conductivity	5.3 W/m*K @10psi (8.5 W/m*K @30psi)	8.5 W/m*K
Thermal Impedance	0.13 @ 10psi	0.04 °C-cm^2/W
Melt temp	45°C	NA

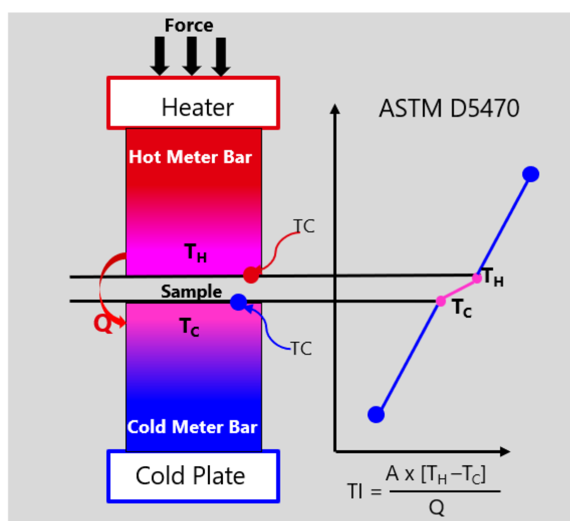

Figure 7. Schematic of Steady State Thermal Test Method

V. Experimental Study

The experimental study was conducted in two parts using a modified ASTM D5470 test standard. Modification consisted of testing the materials at 70°C instead of 50°C. First part was measurement of thermal properties using conventional test equipment, Analysis Tech TIM 1300. Second part was the thermal properties measurement using Thermal Tester ZFW. Two products were tested using both equipment to compare the performance consistency. Specimen dimensions used for this test is shown in Figure 8a and 8b.

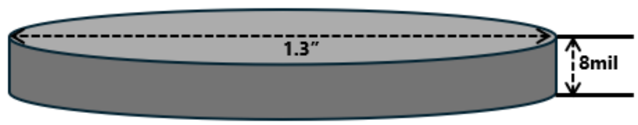

Figure 8a. Sample dimensions used for TIM 1300 tester.

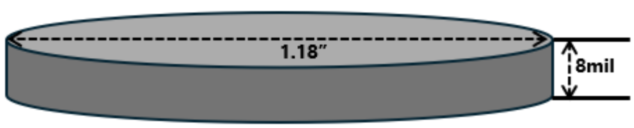

Figure 8b. Sample dimensions used for ZFW TIM tester.

Description of Test Equipment

Analysis Tech TIM 1300 is one of the most commonly used TIM testers in the market. Figure 9 shows a typical image of the tester, while Figure 10 shows a new precision TIM tester from ZFW. Both of these testers used steady state thermal testing ASTM D5470 as described in Figure 7.

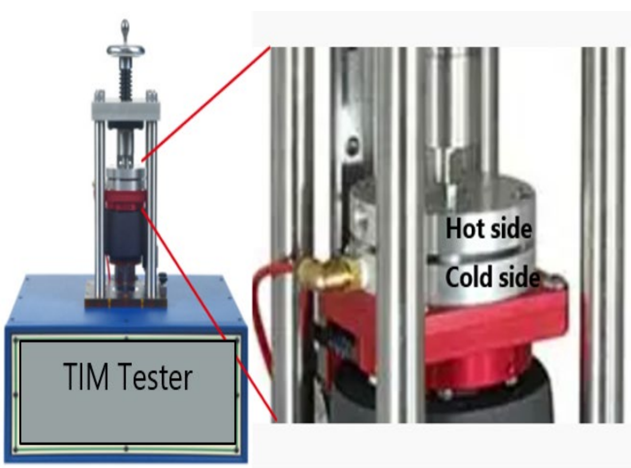

Figure 9. Analysis Tech TIM 1300

TIM 1300 is a simple test set-up designed to measure TI and TC of low to medium conductivity material. "The specimen/sample-under-test is clamped between a pair of parallel conductive surfaces, one heated - one cooled, which imposes a measured heat-flow through the sample. The accurate measurement of the temperature difference across the sample and the induced heat-flow provides the basis for the thermal conductivity measurement. The average sample temperature and clamping contact pressure is automatically controlled based on user-selected values. The effect of contact pressure on thermal performance is easily determined using pressure-batch mode testing" [5]. Samples were exposed to pressure between 10 and 100 psi for TI measurement.

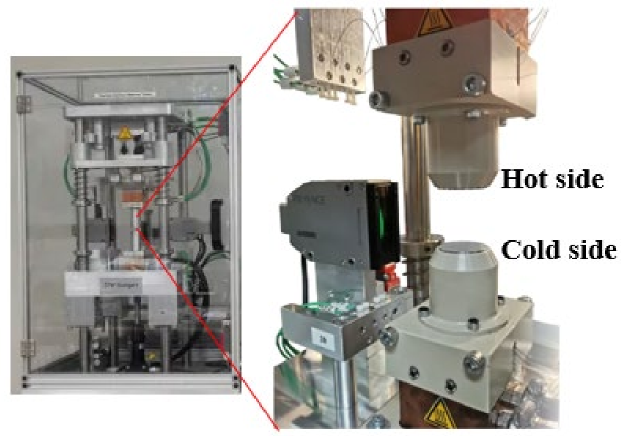

Figure 10. ZFW TIM tester

ZFW TIM tester uses similar concept as TIM 1300 with added precision. "The test stand enables a precise measurement of the (effective) thermal resistance R^{th} of a sample. Due to the high-precision resolution of the gap measurement (measurement of the layer or sample thickness), the thermal conductivity λ of the material can also be determined. By measuring different layer thicknesses, it is possible to determine the contact resistance between the heat-conducting material and the aluminum test surfaces of the device. In general, there are several measurement modes in the TIM tester, depending on the type of material being examined: For low-viscosity samples, the thermal resistance, or the eff. Thermal conductivity as a function of the gap (layer thickness) can be measured without pressure, whereas for solid materials the thermal resistance is determined as a function of the contact pressure" [6]. Samples were exposed to pressure between 5 and 100 psi for TI measurement.

VI. Results & Discussion

Figures 11 and 12 show the results from TIM 1300 and ZFW TIM tester respectively for the two test materials. Result from TIM 1300 shows TI in the negative range which is an artificial number due to lack of precise control over the thickness. This lack of precision becomes more pronounced at higher pressure, lower thickness as we approach minimum bond line thickness. On the other hand, result from ZFW tester shows more predictable TI due to high precision of the test equipment. ZFW allows the bond line to stable through precise control and feedback loop. We also observe THF

5000UT demonstrate much lower TI as compared to Product X at low test pressure.

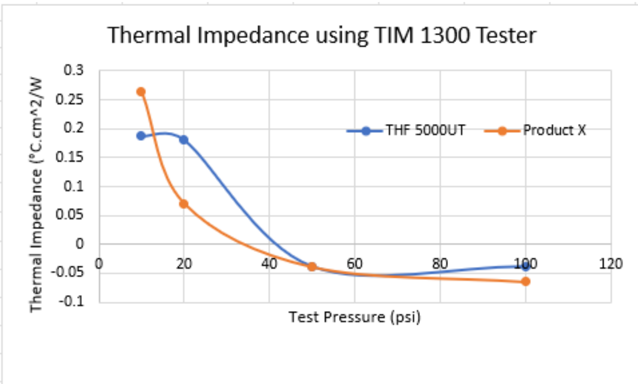

Figure 11. Thermal Impedance from TIM 1300 tester

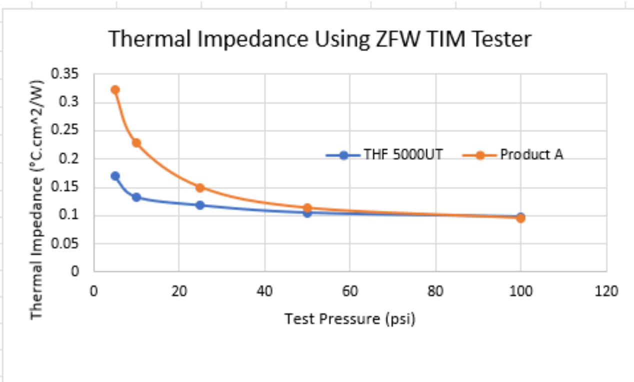

Figure 12. Thermal Impedance from ZFW TIM tester

VI. Summary

The primary objective of this study was to demonstrate the need for a precise measurement system to accurately characterize high performing PCM used in thermal management of high power, low bond line electronics. Authors here do not endorse any type of test equipment but simply demonstrating the effect with readily available lab equipment. It is up to the end user to evaluate test equipment that provides stable and realistic TI results.

It is clear from Figure 12 that we have a reliable way to characterize high performing PCM designed for Next Gen Telecom/Datacom applications. Due to the use of larger (up to 70mmx70mm), sensitive die used in these applications' assembly pressures need to be below 20psi. Based on this study we can say that THF 5000UT performs much better (considerably lower TI) at low pressure providing an alternative to grease or other commercially available PCM.

The current study has been limited to two materials and two test equipment. In order to have higher levels of confidence, this study needs to be expanded to include additional materials and test equipment. We encourage users of PCM for high power electronics thermal management to conduct similar types of study, particularly, suitable for their applications.

Acknowledgment

Authors would like to express their sincere gratitude to Radesh Jewram from Henkel for his contribution in reviewing the paper and making helpful suggestions.

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