Development of a Process Friendly Film for High Performance Thermal Management Applications

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Abstract

Thermal interface materials (TIMs) have been used to transfer heat effectively from a heat-generating device to a cold sink for the last two decades. With advances in packaging technology, the proper selection of a TIM has become more complicated as each application will have different design requirements. The final selection will encompass material properties and process considerations beyond the thermal performance of the material. Compliance, thickness, processing, and response to reliability conditioning are key considerations when engineering the final package. This paper will discuss recent advances in film TIM technology that provide high performance thermal characteristics without conceding other properties. The thermal film described herein will demonstrate low thermal resistance across interfaces of different thickness at various pressures. Furthermore, the material's response to different burn-in temperatures will be characterized. Additionally, the ease of handling and re-workability of the film TIM will be emphasized and compared to other competing high performance formats. This investigation will characterize a new generation of film TIMs that provide the total solution for the thermal engineer.

Key words: thermal interface material (TIM), thermal resistance, reworkability, and film

1.0 Introduction

The evolution of thermal interface materials (TIMs) has resulted from the need to satisfy more demanding thermal budgets.[1] Better heat management has enabled advanced processor and packaging technology and applications have diversified. This diversification has created different formats of TIMs: grease, phase change materials (PCM), pads, films, and gels. A selector guide available from a TIM supplier will steer the engineer accordingly knowing thermal performance, package design, TIM package location, and cost requirements.

Despite the maturity of the thermal interface market, there continues to be a need for higher performance *and* value-added materials.[2] The performance requirement for a TIM now encompasses more than thermal performance. The packaging engineer desires a total solution: low thermal resistance across a bond-line, high thermal conductivity, reworkability, sufficient thickness to accommodate non-planarity, compliance for thermal mismatch, pre-application to a heat sink for speed of assembly, and low cost. Table 1 generalizes the advantages and disadvantages of available TIM formats in consideration of the total material solution.

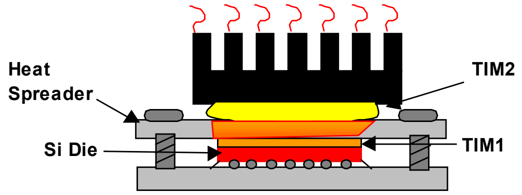

Figure 1: Flip Chip Package for High Performance Applications with Thermal Interface Material

Both grease and PCMs possess low thermal resistance due to their liquid nature at operating temperature and thin bond-line, however, each possess drawbacks. The reliability and messy nature of grease is a concern, whereas the reworkability and low thermal conductivity for PCMs are drawbacks.[3] Pad and film formats offer many advantages from a processing and packaging perspective, but traditionally, their performance is not as high as grease or PCM.[4] There exists a strong need for a high-performance film or pad solution as the strength of those formats makes them useful for typical TIM2 applications. Lastly, the gel format has emerged as a possible improvement to grease's shortcomings, however, it too has drawbacks in application ease and pre-application.[5]

Table 1 : Format Analysis for Total Thermal Solution

	R	K	RW	t	J	P	$
Grease	+	-	+	-	-	-	+
PCM	+	-	-	-	-	+	+
Pad	-	-	+	+	+	+	+
Film	-	-	+	-	-	+	+
Gel	+	-	+	-	+	-	+

+: Favorable attribute
-: Detriment

(R): Thermal Resistance	(J): Compliance
(K): Thermal Conductivity	(P): Pre-applied
(RW): Reworkability	($): Low Cost
(t): thickness	

This paper will describe a novel TIM that offers low thermal resistance and high thermal conductivity, but it also offers the processing advantages of the pad and film formats. The material is most suited for the TIM2 application. The data within this paper will demonstrate a material that can be pre-applied to a heat sink, and it can be prepared from 10-20 mils thick. The thermal performance of the material, despite its thickness, is comparable to grease as a result of good substrate wetting and its compressibility.

2.0 Experimental

2.1 Description of the Materials

Thermal grease (G-1), phase-change materials (PCM-1, PCM-2, and PCM-3), pad materials (Pad-1, PAD-2), and Emerson & Cuming's developmental film (DF-1) were evaluated for thermal performance, ease of use, application, and reworkability. Table 2 summarizes the TIMs that will be evaluated in this investigation.

- G-1 was used received in a 1-cc syringe. PCM-1 was received as a sheet. The organic portion was covered with a release substrate to protect itself from contamination. The foil carrier serves as protective layer and as a rework enabler.
- DF-1 is a developmental film coated onto a carrier liner. It is non-tacky, but it can be provided with a pressure-sensitive adhesive for easy assembly.
- PCM-2 and PCM-3 were also evaluated for ultimate shear strength and reworkability. PCM-2 is traditional brittle, high flow phase change material. PCM-3 is a thin, wax-like PCM coated onto two sides of an Al foil carrier.
- PAD-1, PAD-2 and PAD-3 are representative of "high performance" pads available today. PAD-1 is a BN filled, cured elastomer. PAD-2 is a next generation material filled with graphite for thermal performance. PAD-3 is a rigid TIM with a fiberglass carrier. PAD-1 and PAD-3 offer electrical insulation, but PAD-2 is electrically conductive and offers no insulation.

Table 2: Description of Thermal Interface Materials

	Initial Thickness	**Filler**	**Description**
G-1 (G751)	**Defined by spacers**	**Al, ZnO**	**Thixotropic, silicone, ShinEtsu**
PCM-1 (T725)	**0.11 mm (4.5 mil)**	**BN**	**Tacky (one-side), Foil Carrier, Chomerics**
DF-1 (12425-33-1)	**0.25-0.5 mm (10-20 mil)**	**BN**	**Non-tacky, Free-Standing, E&C**
PCM—2 (HF625)	**0.15 mm (6-mil)**	**BN**	**Non-tacky, Free-Standing, Bergquist**
PCM-3 (Microfaze A6)	**0.14 mm (5.5-mil)**	**BN**	**Non-tacky, double-side coated onto Al foil, AOS**
PAD-1 (T500)	**0.25 mm (10 mil)**	**BN**	**Non-tacky, Compliant, Cured Elastomer, Chomerics**
PAD-2 (PT-H)	**0.25 mm (10 mil)**	**C**	**Tacky, Free-Standing, Polymatech**
PAD-3 (M45)	**0.45 mm (18 mil)**	**BN**	**Non-tacky, Glass Carrier, Denka**

Thermal Property Measurement

2.2-1 Laser Flash Thermal Analysis

The laser flash diffusivity method was used to determine the effective bond-line resistance and conductivity via three-layer sandwich diffusivity measurement. The TIMs were placed under load to a desired torque between T6-6061 Al substrates. Laser energy is used to heat one side of the Al-TIM-Al sandwich, and an IR detector is used to measure the heat flow on the backside of the sample. A mathematical model is used to best fit the half-rise time and determine the sample's diffusivity.[6, 7] With inputs for the thickness, diffusivity, density, and specific heat of the three layers, the thermal

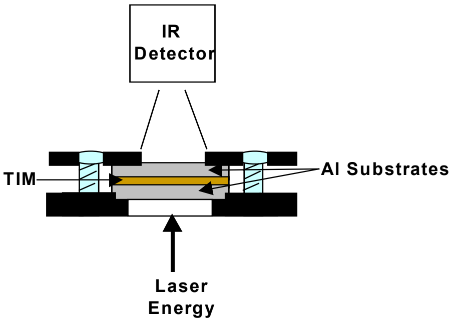

Figure 2: Laser Flash Test Assembly

resistance and thermal conductivity can be determined.

2.2-2 Burn-In and Reliability Procedures

The TIMs under investigation were placed under load with a torque wrench between aluminum coupons of known thickness in the laser flash test jig.

Next, the jig was soaked at a defined temperature for 15 minutes. The assembly was cooled to room temperature prior to testing.

2.0 Reworkability and Handling Assessment

2.3-1 Die Shear Procedure

TIM materials were clamped between a 1-mm thick, 12.5 mm in diameter T6-6061 Al disk and a T6 2024 Al bar. The materials were soaked at 100°C until thermal equilibrium was attained. The samples were removed and allowed to cool to room temperature. Samples were tested to failure on a Dage DS100 bond tester at 500 μm/sec.

3.0 Results and Discussion

3.1 Thermal Properties

3.1-1 Baseline Thermal Comparison vs. Pad TIMs

The thermal performance of DF-1 is compared with today's high performance pad technology in Figure 3. The performance of DF-1 is superior to the PAD-1 and PAD-2 materials despite an initial thickness of 0.25 mm for PAD-1 and PAD-2 as compared to an initial thickness of 0.45 mm for the DF-1. When comparing PAD-3 to DF-1, the initial thickness of the material is equal, however, the thermal performance is drastically different. All of these materials were compliant, but the DF-1 offers the highest compression set after burn-in.

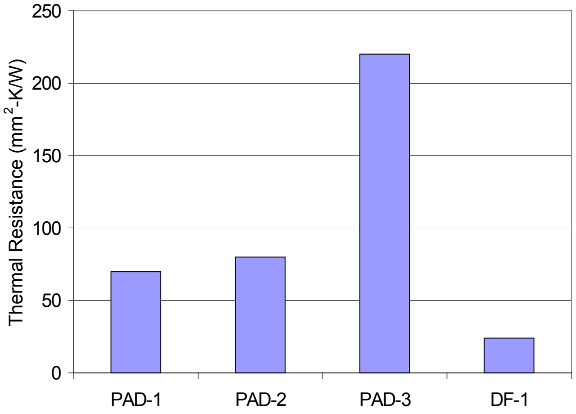

Figure 3: Thermal Performance Comparison of DF-1 to Today's High Performance Pad Technology

3.1-2 Burn-In Response

It is well known that different format TIMs will require different burn-in temperatures in order to achieve the best thermal performance. The most process friendly TIM will possess a low burn-in temperature to prevent a thermal spike during device functionality tests. Table 2 illustrates the desired performance of a grease material. By virtue of its liquid state, the grease material wets the heat producing and heat withdrawing substrates well at room temperature. As a result, the contact resistance is not affected by elevated burn-in as the wetting phenomenon is not affected. Table 2 also illustrates the thermal response of a phase change material. Because it does not wet the substrate below its thermal transition, the thermal resistance is high when applied and tested without a burn-in. This phase change material has a transition temperature of 55°C, however, the data collected indicates that a burn-in temperature of 100°C is more desirable for better performance. The DF-1 also requires an elevated burn-in prior to use for best thermal performance. DF-1 shows demonstrates low thermal resistance at low burn-in temperatures, and the thermal resistance is not improved substantially at 100°C. Despite its advantageous film format, it appears to wet the substrate well at low temperature.

Table 3 : Resistance (mm^2-K/W) as a Function of Burn-In Temperature

	25°C	**60°C**	**100°C**
G-1	**10**	**10**	**8**
PCM-1	**NA**	**90**	**45**
DF-1	**NA**	**25**	**24**

NA = Not acceptable burn-in condition

3.1-3 Thermal Performance Comparison

The thermal performance of DF-1 and G-1 are compared in Figure 4 below. By plotting resistance vs. thickness, the thermal conductivity of the TIM can be calculated by inverting the slope for a linear least fit square approximation. Furthermore, the contact resistance can be determined as the y-intercept.

As a TIM, grease is recognized as a strong performer due to its ability to compress down to thin bond-lines under load. The thermal resistance pathway is reduced when the bond-line is minimized. Figure 4 illustrates the low thermal resistance of G-1. The variation in bond-line thickness was achieved with different sized spacer materials. The thermal conductivity of the material was calculated to be 5.5 W/mK. The thinnest bond-lines were achieved without spacers.

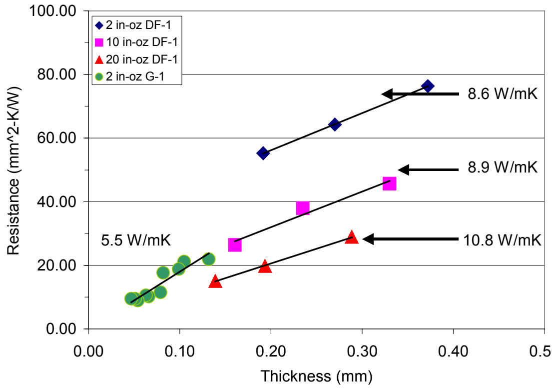

Figure 4: Thermal Performance Comparison of DF-1 and G-1

In comparison, the DF-1 also exhibits very good thermal resistance, but the results are at much thicker bond-lines. The G-1 material has a resistance of 10-20 mm^2-K/W across a bond-line of 0.05-0.1 mm, whereas, the DF-1 exhibits a thermal resistance of 15-29 mm^2-K/W from 0.15 to 0.30 mm. It is advantageous to have a compressible material with low thermal resistance across thick bond-lines. DF-1 will accommodate non-planarity and surface irregularity as a result of these properties. It could potentially accommodate different bond-line heights.

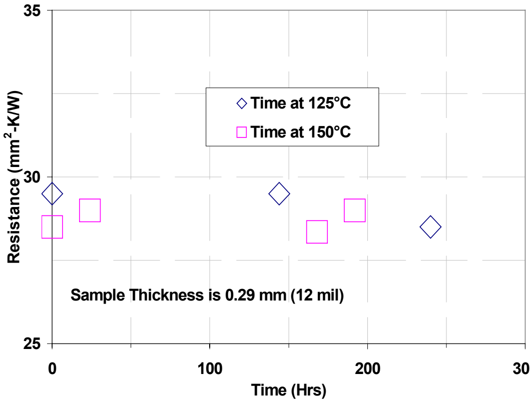

Figure 5: Thermal Resistance after Exposure to 125°C and 150°C Soak for Extended Time

Equivalent performance to grease is obtained when a higher load is applied to the material. Higher applied loads are not uncommon when handling solid film formats. The plot indicates that a higher load applied to the bond-line will produce a higher thermal conductivity. By increasing the torque on the four screws from 2 in-oz to 20 in-oz, the conductivity of the material increases 25%. As a result of the increased pressure, particle-to-particle contact is increased, but more importantly, the contact resistance is reduced.

3.1-4 PSA and Reliability Assessment

For ease of handling and assembly, it is advantageous to pre-apply the film to a heat sink at the heat sink manufacturer. The DF-1 was evaluated with a pressure sensitive adhesive and it was soaked at elevated temperature to know its ability to withstand harsh conditioning. DF-1 was soaked at 125°C, and it was tested successively at 144 and 240 hrs without disassembling the test jig. Next, the sample was held at 150°C for up to 96 hours. The results in Figure 3 indicate that the TIM's ability to transfer heat is not compromised by elevated temperature soak below 150°C.

Furthermore, the addition of the PSA does not compromise the thermal performance of the film. The thermal resistance of the film is 29 mm^2-K/W at a thickness of 0.30 mm (12 mil). This sample was compressed 34% as its original thickness was 0.45 mm (18 mil). Compression is calculated as shown below:

$$\frac{\text{(Initial Thickness-Final Thickness)}}{\text{Final Thickness}} \quad \text{x } 100$$

This allows for high volume pre-attach and enables automated assembly. Also, the PSA does not flow or pump-out during the high temperature conditioning as is evident by the stability in the bond-line thickness.

3.1-5 Resistance vs. Compression

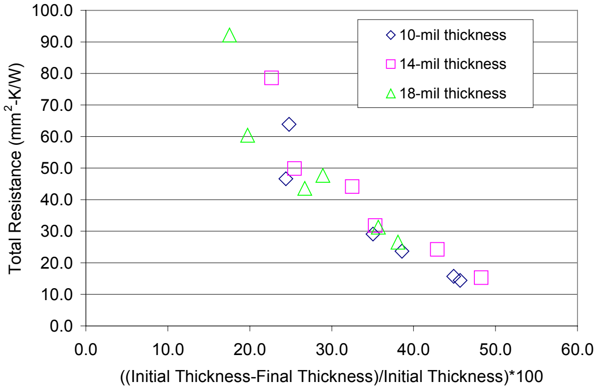

Figure 6: Thermal Resistance of DF-1 as a Function of Compression

It is well known that the load applied to the interface affects the thermal resistance across a bond-line. An increase in the applied load will reduce the thermal resistance. The primary modes are through improved wetting of the substrate and improved particle to particle contact. The increased load also serves to remove any air that exists within the bond-line. Air present in the bond-line will negatively impact the contact resistance.

Figure 6 illustrates the change in thermal resistance as a function of compression. Three DF-1 samples were prepared of different final film thickness by adjusting the knife height during the coating process: 0.25 mm (10 mil), 0.35mm (14 mil), and 0.45 mm (18 mil). The thermal resistance was determined for each of these films under different amount of compression. Applying different torque pressure prior to the heat soak varied the % compression. As the pressure was increased, the % compression for DF-1 also increased. Furthermore, the thermal resistance across the bond-line was reduced.

This result is advantageous when considering the non-planarity that can exist at the TIM2 level. Variation in heat sink extrusion and different geometry creates a need for interface materials of different thickness. The formulation is robust in its composition such that different thickness films can be coated.

3.2 Reworkability and Handling Assessment

3.2-1 Comparison vs. PCM-1 and G-1

DF-1 and PCMs -1, -2, and -3 were punched to 12.7-mm disks and attached to the Al substrates via their inherent tack. Assembly was simple, and as a result of their tack, both materials can be pre-applied to a heat sink prior to delivery to the packaging house. The G-1 was applied in a blob of material. Excess grease squeezed out beyond the Al disk boundary; this could be addressed with proper dispense controls.

All materials flowed beyond the 12.7-mm disk dimension during heat soak.

- The PCM-1 organic portion squeezed out and wicked along the sides of the Al disk and foil carrier. Thus, the material did not cleanly release from both substrates. By virtue of the foil carrier, PCM-1 is an improvement over traditional PCMs with respect to reworkability. However, the thermal resistance of this material is quite high for a phase change material and this may result from the foil carrier-substrate interface. PCM-2 and PCM-3 also flowed beyond the diameter of the Al disk. All materials flow % were comparable.
- DF-1 also squeezed out beyond the disk as a result of a large compression. The material was easy to remove from the substrate as it maintained its integrity after heat soak. The DF-1 film sample was the most rework friendly material evaluated.
- Excess G-1 required solvent for removal from the substrates. This proved to be the messiest TIM for cleaning.

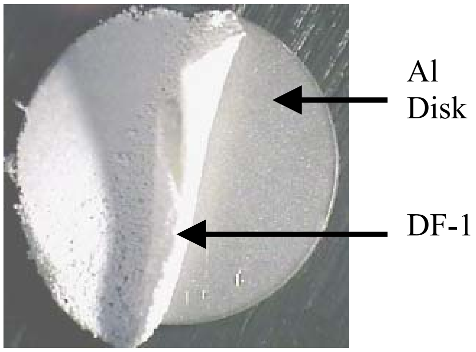

Figure 7: DF-1 Folded onto Itself during Disassembly Demonstrating Ease of Rework

3.2-2 Reworkability Assessment

Some thermal interface users need reworkability to insure that expensive devices or components can be disassembled if the device fails functionality testing. For an assembly that includes direct attachment of a heat sink to a chip, the ultimate shear force needs to be small such that the die is not damaged during removal. A die shear tester was used to evaluate the force required to shear the two Al substrates apart after heat soak (Figure 8 and Figure 9). As one can see, not all materials are equally easy to rework. Within the class of PCMs, there is a great difference in reworkability. The PCM-1 is marketed as a reworkable, however, its ultimate shear force was higher than PCM-3. PCM-3 is not marketed as a reworkable material. PCM-2 had the highest rework force, and it is most typical of a traditional wax-like PCM. G-1 required a small amount of force for removal as a result of good surface wetting and atmospheric pressure. DF-1 was

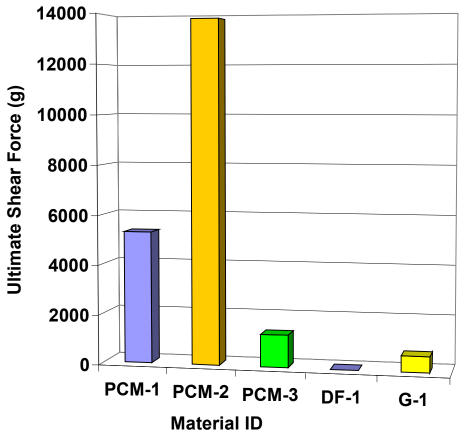

Figure 8: Ultimate Shear Force to Separate Al Disk from Al substrate after Heat Soak at 100°C

the easiest material to rework as illustrated in Figure 9. It released cleanly from one substrate, and the material was peeled away from the disk.

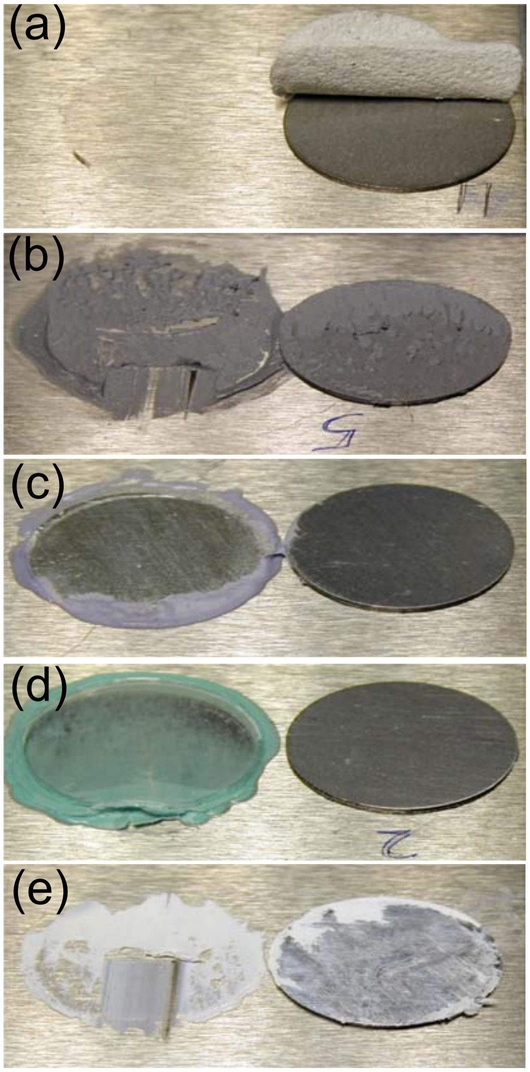

Figure 9: Illustration of Reworkability Assessment for (a) DF-1, (b) PCM-3, (c) PCM-1, (d) PCM-2, and (e) G-1

4.0 Conclusions

4.1 Thermal Performance

The thermal performance for DF-1 is very good at thick cross-sections. When compared to G-1 grease, it can have equivalent performance when a higher load is applied. The material wets well at a low burn-in temperature despite its solid state. DF-1 was shown to be superior to the reworkable PCM-1 before and after high temperature burn-in.

DF-1 is also very suited for applications requiring a thicker bond-line or a variable height bond-line. The thermal resistance is best when the material is compressed at 30-40% its original thickness, but it shows very good performance at lower compression.

4.2 Process Friendly

DF-1 offers processing advantages via its film format. The material can be handled easily, and it can be punched and pre-applied to a heat sink. Also, the material is very easy to rework without the use of solvent.

References

1. Vukovic, A., "*Power Density Challenges of Next Generation Telecommunication Networks"*, in *Electronics Cooling*. 2003.
2. Azar, K., "*Is Thermal Activity on the Rebound?"*, in *Electronics Cooling*. 2003.
3. AMD, *AMD Athlon 64 Processor Thermal Design Guide*. 2003. p. 57.
4. Collins, A., Cheng, Chih-Min. "*Development of a Reworkable Film for High Performance Thermal Management Applications*." in *International Microelectronics and Packaging Society*. 2002. Denver.
5. Dean, N., "*Materials for Thermal Management: Properties and Processes*, in *Advanced Packaging*." 2003. p. 15-20.
6. Chiu, C., Maveety, J., Varner, L. "*Thermal Conductivity and Resistance Measurements of Three-Layer Composites with Solders"*. in *2000 International Symposium on Microelectronics*. 2000.
7. Campbell, R., Smith, S., "*Flash Diffusivity Method: A Survey of Capabilities"*, in *Electronics Cooling*. 2002.