Liquid Metal Embedded Elastomers (LMEE) as Low-BLT Thermal Interface Materials

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SUMMARY

Achieving reliable thermal interfaces with low bondline thickness (BLT) is a difficult challenge in the thermal management industry. Mismatched coefficients of thermal expansion between the substrate, die and heat spreader lead to warpages during thermal cycling which the thermal interface material (TIM) must survive. Common failure mechanisms of the TIM during thermal cycling are i) when the warpage exceeds linear and nonlinear maximum strain capacity of the TIM leading to tearing or ii) when the interfacial stress between the TIM and die/IHS exceeds the maximum adhesion stress leading to delamination. To combat this issue, in this study, we sought to develop a TIM that can achieve high strain at break and high adhesion, while maintaining low thermal resistance. Our formulation, based upon the liquid metal embedded elastomers (LMEE) architecture, combines polymers with a high volume fraction loading of liquid metal inclusions. While the TIM presented in this manuscript needs to undergo further reliability testing before being deployed in-package, it represents a step toward breaking the fundamental limitations imposed by conventional materials.

1. INTRODUCTION

The first, and arguably most critical area that heat must pass through when dissipating from high-power-density semiconductors is the thermal interface material (TIM) that adheres the die to its heat spreader, called the TIM1 material. Desirable properties of TIM1 materials include: easy application, low thermal resistance, high electrical resistivity, and thermomechanical robustness, as is typically tested using thermal cycling and bake tests. Traditional choices of TIM1 include gap fillers (thermal pads), thermal greases, solid TIMs (such as sintered silver and indium alloys), and liquid metals (such as eutectic gallium-indium).[1] However, as power densities in semiconductor packages have increased dramatically in recent years, thermal engineers are finding it difficult to obtain TIMs that have suitably low thermal resistance and can survive the required thermal cycling profiles. Recently, researchers have proposed using liquid metal embedded elastomers (LMEEs) [2] as thermal interface materials,[3] to develop a TIM1 LMEE suitable for the most demanding of applications.

2. Material Mechanical Characterization

For this study, we developed a silicone-based polymer that has high strain at break and high adhesion. Using the developed polymer, we fabricated a liquid metal embedded elastomer (LMEE) with high stretchability and adhesion to develop a material for TIM1 that can attain a low BLT. To achieve a feasible material for a TIM1 application, several optimizations were required, but here we will focus on the parameters that are most relevant to obtaining reliable low-BLT TIM interfaces with LMEEs.

Liquid metal droplet size influences the thermal performance and mechanical properties of LMEEs. We fabricated the LMEE with an average droplet size larger than the BLT, to archive optimal thermal properties. [4] We measured the droplet size of the LMEE using a Zeiss optical microscope combined with image-processing software. Next, we evaluated strain at break of the LMEE by stencil-casting dog-bone specimens (500 µm thickness) and stretching them in a materials testing machine (Mark-10 ESM303) at a rate of 50 mm/min, until mechanical failure of the TIM.

The average droplet size of the LMEE was approximately 100 µm in diameter, following a polydisperse distribution (**Fig. 1, left**). This allows each droplet to compress significantly at low BLT (<40 µm), allowing the interfacial thermal resistance to be low. In this study, we were able to achieve LM loading of >60 vol%, without compromising the stretchability of the TIM (**Fig. 1, right**). As the TIM stretched, each liquid metal droplet deformed with its surrounding polymer matrix without rupturing, allowing the TIM to achieve maximum strain at break >350%, with a relatively low elastic modulus of 200-300 kPa.

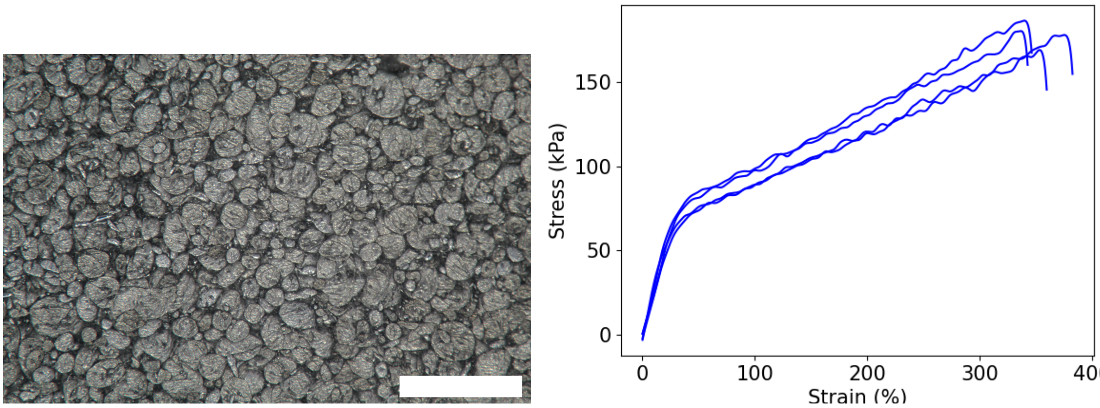

Figure 1. LMEE Characterization. Left: microscopy, showing average droplet size ~100 µm. Scale bar is 500 µm. Right: uniaxial tensile testing of the LMEE in a stretch-to-failure test. Strain at break typically is in the range of 300-400% (engineering strain).

3. Thermal/Mechanical Characterization

An important criterion for selecting a TIM1 inside semiconductor packaging is the performance during thermal cycling. During the thermal cycling reliability test (JEDEC A106B), the TIM undergoes strain due to changes in the BLT. To simulate the behavior of TIM inside semiconductor packaging, we characterized the LMEE's thermomechanical properties using a ASTM D5470 style test setup (Nanotest, TIMA 5; **Fig. 2**). First, we applied the LMEE in an emulsion state and then compressed it in between two testheads at 20 psi. To maintain a controlled BLT of 20µm throughout the application and curing process, we used a 20µm diameter . Next, the upper hot plate and lower cooler temperatures were simultaneously increased to achieve a TIM temperature of 110 °C. We allowed the material to cure under constant pressure of 20 psi for 3 hours. After curing, we reduced the testheads temperature to allow the temperature of the TIM layer to return to room temperature overnight. Finally, we used the TIMA software to automatically subject the LMEE to repeated strains (from 50% to 150% strain) at a rate of 15 cycles per hour for 50 cycles, while measuring thermal resistance.

When subjected to strains, the thermal resistance increases when the BLT goes from ~25µm to ~50µm (**Fig. 2, Right**). However, the effective thermal conductivity, measured by calculating BLT/R_{th} (single point effective thermal conductivity) remains consistent at both low and high BLTs (25 µm and 50 µm). Additionally, the TIM returned to the same thermal resistance value when the BLT goes back to nearly the initial BLT, suggesting that the TIM did not delaminate or tear during the mechanical cycles. Delamination or tearing would manifest in higher thermal resistances, as the interfacial thermal resistance would be higher due to decreased phonon and electron transport through the introduced air gaps.

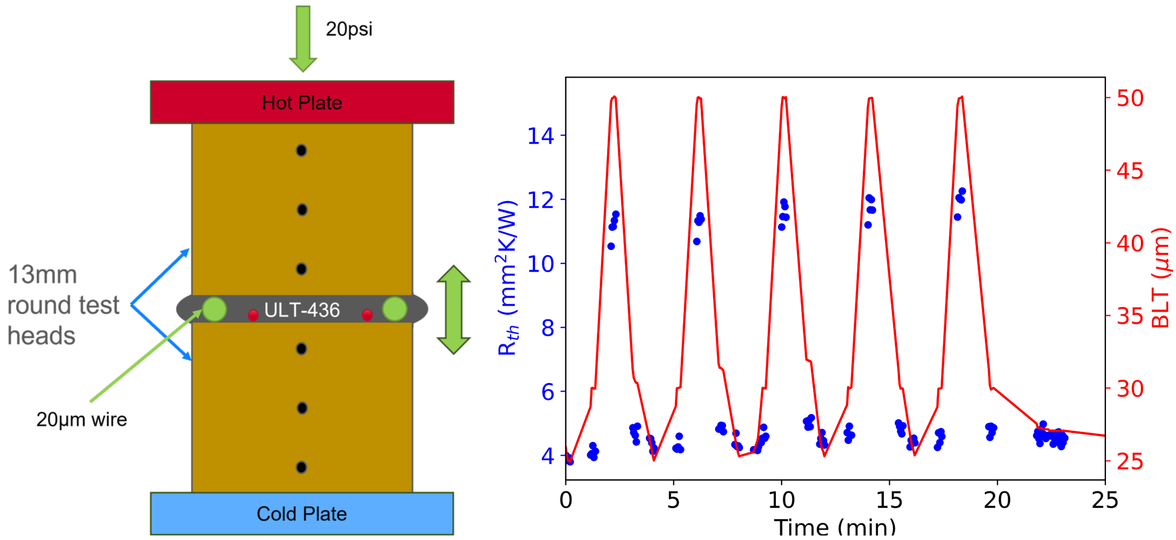

Figure 2. Repeated stress testing, with LMEE cured in a TIMA test setup. Left: schematic of test setup. First, 20 psi was applied to the TIM, allowing TIM to attain 20 µm BLT. Then, heat was applied to cure TIM. Finally, the TIM was repeatedly stressed from 50 to 150% strain, with thermal resistance periodically recorded throughout. Right: thermal resistance data for first 5 cycles from 50 to 150% strain.

After 50 cycles, the average R_{th} in the low-BLT (unstressed) state remained lower than 5 mm^2.K/W, indicating the TIM maintained its mechanical integrity (**Fig. 3**). In future experiments, we plan to expand our stress experiments to study the relationship between strain magnitudes and increases in thermal resistance and cycles to failure, to quantify the damage profile of the TIM.

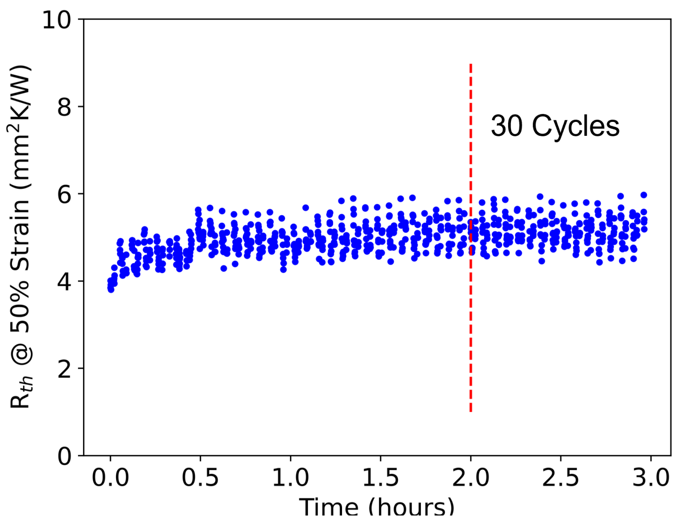

Figure 3. Thermal resistance of LMEE at 50%, representing the low-strain portion of multiple cycles from 50% to 150% strain.

Finally, the most important evaluation step in a typical TIM qualification process is characterization of the TIM inside semiconductor packaging and evaluating the reliability performances. To achieve this, we used the same LMEE formulation in a thermal test vehicle (TTV) with a 10 x 10 mm^2 die size (Nanotest NT16-TTV5; **Fig. 4**). The LMEE was pneumatically dispensed onto the die in an X pattern using a CNC dispenser (**Fig 4. left**), followed by a snap cure process (**Fig. 4 middle**) where a top heated plate applied pressure (40 psi) and heat (150 °C) simultaneously to assemble the TTV. The snap cure procedure was followed by an oven cure of 150 °C for 1 hour, to ensure full curing of the lid sealant and the TIM. The thermal resistance of the TIM layer was measured by running the TTV heaters at 10, 20, and 30 W, while simultaneously measuring the die temperature using internal thermistors and measuring the lid temperature using a thermocouple inserted in a milled hole in the lid. For this study, we report the estimated Rth at the corners, center, and average across the die; the reported means and standard deviations are taken across all tested powers to present a more conservative uncertainty estimate that is more representative of actual power usage. Each value was obtained by subtracting the estimates of lid thermal resistance from the junction-case thermal resistance.

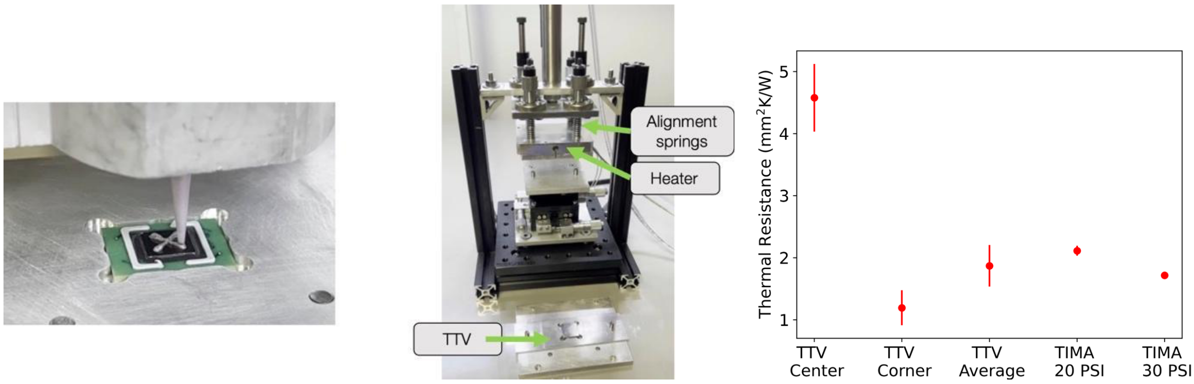

Figure 4. TTV characterization. Left: dispensing LMEE onto a TTV die. Middle: TTV snap cure setup. Right: Measured Rth of LMEE inside of a TTV, using die temperatures at the center and four corners, compared to TIMA thermal resistance measurements.

We measured a center R_{th} value of 4-5 mm^2.K/W and an average corner R_{th} (average of four corners) of 1-1.5 mm^2.K/W. We suspect the differences in thermal resistance at center vs corner is either a result of in-plane thermal leakage which results in cooler corner temperatures, or inhomogeneities in the LM distribution after compressing the TIM to low BLT. This will be further investigated using thermal simulations and confocal sound acoustic microscopy (CSAM). Additionally, we compared the average thermal resistance of all 5 TTV measurements (~2 mm^2K/W) with the thermal resistance measurement using TIM Analyzer instrument (TIMA5) at 20 psi and 30 psi. We found that the TTV average thermal resistance matched the TIMA thermal resistance values (**Fig. 3, Right**).

4. CONCLUSIONS

This study investigated how LMEE could be adapted to serve low BLT TIM1 semiconductor packaging applications. Specifically, we presented a highly adhesive LMEE that could achieve strains as high as 350% before failure. This gave the TIM a significant safety factor above our experimental stress cycling from 50 to 150% strain, allowing a 20 μm interface to survive cyclic loading with the increase in thermal resistance being approximately 25%. As we moved to TTV characterization, we found that the average thermal performance was similar to results obtained using a D5470 thermal measurement device. Future investigations include testing with transparent glass test vehicles (replacing IHS with glass to study the LM distribution throughout the compression cycle), cross-sectional analysis, and simulations to investigate the non-uniform thermal resistance, in addition to TTV reliability testing (thermal shock test, accelerated stress testing, etc.).

5. REFERENCES

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