# Development of an Extremely High Thermal Conductivity TIM for Large Electronics Packages in the 4th Industrial Revolution Era

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***Abstract*—The capability and diversity of high-performance microprocessors is increasing with each process technology generation to meet increasing application demands. The cooling designs for these chips must deal with larger temperature gradients across the die than previous generations. Dissipation of the thermal energy from heat generating parts to a heat sink via conduction occurs through a thermal interfacial material (TIM). One of the most important parameters of TIMs is their thermal conductivity that impacts the efficiency of the thermal management. Therefore, in this study, three new different types of TIMs with high thermal conductivity (> 20W/mK) were examined.**

**In this paper, workability and reliability test results will be shown for metal sheet TIM (60W/mK), graphite sheet TIM (24W/mK) and silver (Ag) sintered TIM (50W/mK) materials. All test package sizes are covered with 52.5-mm body size or 45-mm body size for large package with > 45-mm body size in a flip chip ball grid array (FCBGA) package. The reliability test items are high-temperature storage (HTS) @ 150'C 1000hrs, temperature cycling (TC) 'B' 1000X and unbiased highly accelerated stress test (uHAST) for 96hrs. Open/short (O/S) test, scanning acoustic tomography (SAT) or X-ray analysis data are reported. Post reliability test, lid pull test results will be shown as well.**

***Keywords-component; Metal sheet TIM, Graphite sheet TIM, Ag sintered TIM, Lid attach process***

## I. Introduction

As the electronics industry needs more advanced semiconductors to meet the demanding requirements of current and future end-application, there is considerable engineering effort to ensure these advanced semiconductors can maintain their performance for the environments they will encounter during their lifetime [1]. A major consideration for success is the overall robustness of the semiconductor package. The semiconductor package must provide the five functions mainly: protection, power distribution, signal distribution, design and test and thermal management [2].

Among these considerations, thermal management of chip-based electronic devices is one of the largest bottlenecks to increased performance and integration density. Although the energy per operation is increasing, more and more transistors in the same area increases the density of dissipated power to an unacceptable level that threatens the current rate of progress of the industry. Thermal interfacial materials (TIMs) play a key role for the heat dissipation at all levels within a microsystem [3].

TIMs are used between die and heat-spreader to provide a good thermal path for heat transfer in the electronics package application. There are two critical functions of TIMs: (1) to dissipate heat to allow higher processing speeds and (2) to absorb strain resulting from the mismatch of coefficients of thermal expansion (CTE) of the die, substrate and the integrated heat sink and heat spreader (lid) during temperature changes in assembly processing and usage. There are several material solutions for TIMs: adhesives, gels, greases and phase change materials. Most of TIMs consist of a polymer base, such as an epoxy or silicone resin with conductive fillers such as aluminum, alumina, zinc oxide or silver [4]. The advantage of these materials is high elongation, high strain with good workability and a large range of processability. The disadvantage of these materials is a thermal conductivity of less than 10W/mK in despite of the loading of conductive fillers. In addition, the thermal degradation and pump out phenomena in workability level and post reliability tests occur as shown in Fig. 1. To meet the increasing demand of heat dissipation in high performance microprocessors, new TIMs and technologies are needed continuously.

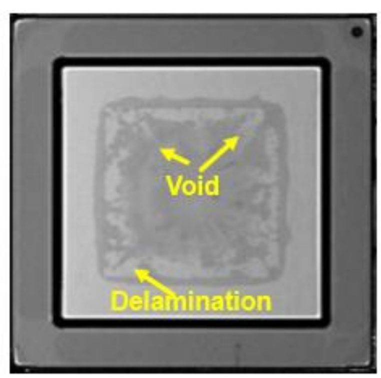


Figure 1. Confocal scanning acoustic microscopy (CSAM) image of gel type TIM. White spot indicates voids and delamination at die area post reliability test (high-temperature storage (HTS) 1000 hrs) on 52.5-mm body size.

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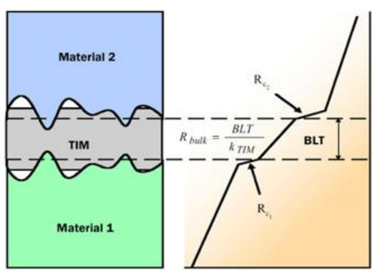
As shown Fig. 2, heat transfer between the two surfaces can be improved by applying a thermal interfacial material. TIMs are typically used to fill the gap, remove air and improve the heat transfer between two surfaces. The ability of a material to resist heat flow is termed thermal resistance. The total thermal resistance at the interface between two materials is a sum of the resistance as a result of the thermal conductivity of the TIM and the contact resistance between the TIM and the two contacting surfaces. It is critical to minimize contact resistance to improve the lid attach process across the interface. This can be managed by reducing the bond line thickness and employing a TIM with maximum thermal conductivity as well as reducing the contact resistance at each surface in Fig. 2 [5].

To further minimize the thermal resistance between two surfaces, new TIMs with high thermal conductivity are required.




$$R_{jc} = \frac{BLT}{k_{TIM}} + R_{c1} + R_{c2}$$

Figure 2. Schematic TIM between contacting surfaces.

Polymer-based materials are used as a TIM for heat conduction across the interface. This is mainly due to the ease of application and lower material and manufacturing cost compared to a metal sheet TIM, graphite sheet TIM, or silver (Ag) sintered TIM. Since filler particle amount and size in the polymer matrix are the limitations, good heat conduction requires intimate contact between the filler particles, filler to silicon and filler particles to the lid. All these contacts cause high contact resistance. Therefore, it is easy to understand why the new type TIM has higher thermal conductivity than a polymer-based TIM [6].

In this paper, three new different type TIM with high bulk thermal conductivity (metal sheet TIM (60W/mk), graphite sheet TIM (24W/mk) and Ag sintered TIM (50W/mk)) were evaluated through workability test, characterization and reliability tests, see Table II. These test results are intended to determine the process performance, the reliability performance on the FCBGA package and to provide findings.

## II. Experiments

### *A. Test Vehicle Information*

Test vehicles (TVs) of flip chip ball grid array (FCBGA) with package sizes of 45x45 mm and 52.5x52.5 mm were designed with same printed circuit board (PCB) stack-up structure. The copper pillar (CuP) bumps have a minimum bump pitch of 165 µm and 200 µm. The silicon (Si) node was a daisy-chain for easy Open/Short test capable. The basic information is shown in Table I. In addition, the target requirements of the TVs are as follows.

- TIM coverage > 90% at T0
- No electrical failures after MSL4, uHAST 96 Hrs, TCB 1000X and HTS 1000 Hrs

TABLE I. Specifics of the Test Vehicles

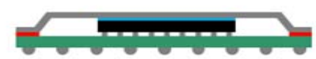
| **Category** | **Test vehicle** | |
|---|---|---|
| | **FC 52.5** | **FC 45** |
| Package size (mm) | 52.5x52.5 | 45x45 |
| Package structure |  | |
| Die size (mm) | 25.6x25.6 | 19x19 |
| Min pitch (µm) | 165 | 200 |
| Bump type/Height (µm) | Cu pillar/60 | Cu pillar/90 |
| Passivation | PI | PI |
| Substrate thickness (µm) | 1.0 | 1.0 |
| Heat spreader | 1.5T Ni/Cu single piece lid | 1.0T Ni/Cu single piece lid |
| **TIM** | **Metal sheet TIM Graphite sheet TIM** | **Ag sintered TIM** |

TABLE II. Information of New High Thermal TIM

| TIM | Metal sheet TIM | Graphite sheet TIM | Ag sintered TIM | Polymer base (Ref.) |
|---|---|---|---|---|
| Thermal conductivity (W/mK) | 60 | 24 | 50 | ~5 |
| Composition | In10Ag | Graphite | Ag sintered with epoxy resin | Alumina filler with silicone resin |

### *B. Assembly process on FCBGA package*

At the wafer saw process, a 3x3 array for 45BD or 4x4 array for 52.5BD was separated by package body size. In the chip attach process, sawn dies were attached with water-soluble flux onto the PCB. Then the reflow process proceeded for soldering between bump on die and bump pad on the PCB. To check wettability and solderability, de-lid inspection was performed. After the chip attach process, flux cleaning was applied in a flux cleaning machine. For low humidity and low package warpage at room temperature, prebake was conducted in the oven. At the underfill process, underfill was dispensed at the die edge line with good flowability and without void and abnormal marks and then underfill cured in the oven.

For the lid attach process, the proposed polymer solution TIM was dispensed on the die area and the other adhesive material for the lid was also dispensed using a special pattern to get good coverage. Then, the heat spreader was loaded on the TVs. For TIM and lid adhesive material curing, all packages used the box oven.

At the BGA attach process, the BGA ball was attached on the PCB ball pad with a water-soluble flux and the reflow process performed for BGA soldering.

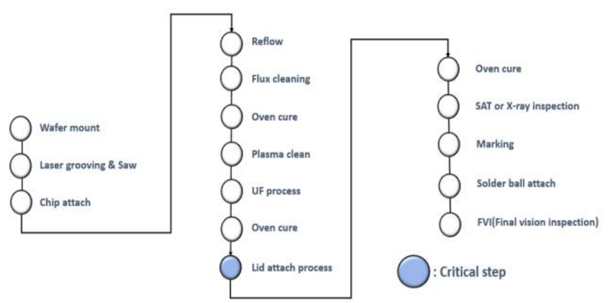



Figure 3. Assembly process for FCBGA package.

### C. *Lid Attach Process for three different TIM*

The lid attach process for the three different type TIMs, different TIM samples and different lid attach process conditions are summarized in Table III.

- Metal sheet TIM: The metal sheet TIM has longer elongation than the polymer type TIM due to the ductility property of metal, despite the high modulus, so the metal sheet TIM has larger coverage in the post reflow process [7]. To reduce voids and overflow, an indium silver (In10Ag) composition was selected with a liquid phase point of 230°C. Compared to the peak temperature of normal reflow process (260°C), the low peak temperature could be applied to the solder joint between the die and the lid. The special backside metallization (BSM) treatment was needed on the die and the heat spreader (lid) to solder the metal TIM between the die and the lid. A gold (Au) treatment using a sputter process or Ag treatment using spray process on the die and the lid were considered. The lid adhesive material was dispensed on the top of the PCB and metal sheet TIM (In10Ag) with 200-µm thickness and laminated on the die area. Then, the lid adhesive material was cured with a Holding Fixture Medium (HFM) in the oven. For soldering the metal sheet TIM, the flux-less reflow machine with formic acid gas or the mass reflow machine was used to reduce the overflow phenomena and package warpage behavior under post process. For the flux-less reflow evaluation, the key process parameters were peak temperature, dwell time and formic acid gas amount for higher wettability during soldering at the low process temperature. This information was helpful for overflow ration reduction. For the mass reflow evaluation, key process parameters were temperature, dwell time and total pass time during reflow at the high process temperature. This approach was better for higher adhesion than flux-less reflow using specially designed fixtures.
- Graphite sheet TIM: The graphite sheet TIM is composited of a multi-stack laminate of graphite filler with flexibility in vertical direction without an adhesion layer. With this approach, it is possible to achieve high thermal conductivity. The lid adhesive material was dispensed on top of the PCB and the graphite sheet TIM with 250-µm thickness was laminated on the lid. Then, the lid adhesive material was cured with an HFM in the oven. Due to the potential for tearing, a small loading force was needed when laminating the heat spreader.
- Ag sintered TIM: The Ag sintered TIM was made of high amount of Ag filler in an epoxy resin. To compare with polymer-based silicone resin, there is no limitation to make the thermal conductivity high. The Au BSM treatment was needed on the die and the lid because of Ag sintered TIM soldering between the die and the lid. The lid adhesive material and Ag sintered TIM were dispensed on top of the PCB and on the die. Then, both were cured with an HFM in the pressure oven. By using a pressure oven, void occurrences were reduced. Also, the 2-step cure was helpful to reduce TIM voids and wrinkling of lid adhesive material for minimal (stable) package warpage.

TABLE III. LID ATTACH PROCESS FOR NEW TIMS

| | **Metal sheet TIM** | **Graphite sheet TIM** | **Ag sintered TIM** |
|---|---|---|---|
| 1 | Packages with metallized die after underfill cure | Packages after underfill cure | Packages with metallized die after underfill cure |
| 2 | Adhesive material dispense | Adhesive dispense | Adhesive & TIM dispense |
| 3 | Place metal sheet TIM onto die | Place graphite sheet TIM onto Lid | Lid placement & press |
| 4 | Lid placement & press | Lid placement & press | Adhesive cure |
| 5 | Adhesive cure | Adhesive cure | NA |
| 6 | Reflow for soldering | NA | NA |

NA = not applicable

## III. Results and Discussion

### A. Workability test

For coverage inspection of the metal sheet TIM, graphite sheet TIM and Ag sintered TIM, a C-mode scanning acoustic microscopy (CSAM) was used to evaluate the joints. CSAM analysis is nondestructive analysis technique engaging ultrasound at different frequencies. In the deflection mode, voids and delamination and non-wet coverage areas are observed as white patches against the darker background and can be verified by the inverted phase of the reflected waveform. X-ray was used to check for voids and overflow for metal sheet TIM. The coverage of metal sheet TIM was 100% at the die. White spots indicate voids and dark black indicates overflow in Fig. 4. There is no delamination with a good joint between the TIM and the lid. Regarding the voids, less than 10% were detected on the die by X-ray inspection. The overflow is also shown in Fig. 5.

The graphite sheet TIM coverage was 100% at the die. There are no voids, but the density of the TIM is different between the center and the edge of die in Fig. 6. The result is no adhesion layer and the tackiness layer only remains on one side layer.

The Ag sintered TIM coverage had 100% at the die. There is some void at edge of die, but circle shape was detected by package warpage in Fig. 7. This was caused from the small resin amount by adding rich filler amounts for high thermal conductivity. During TIM and lid adhesive cure, the circle shape occurred from lower adhesion from resin shortage under different thermal stress.

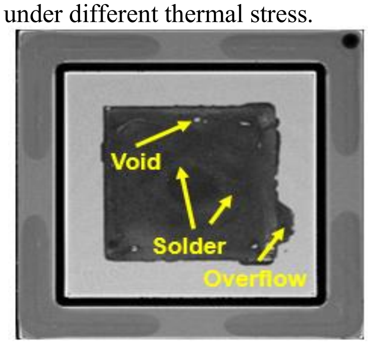



Figure 4. CSAM image of metal sheet TIM (In10Ag). White spots indicate voids. Dark black indicates overflow. 100% TIM coverage.

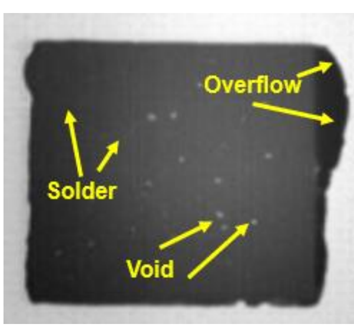



Figure 5. X-ray image of metal sheet TIM (In10Ag). White spots indicate voids. Dark black indicates overflow. 100% TIM coverage.

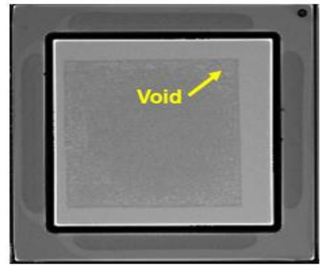



Figure 6. CSAM image of graphite sheet TIM. White spots indicate voids. 100% TIM coverage.

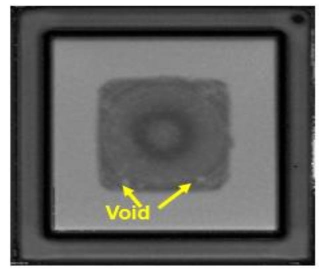



Figure 7. CSAM image of Ag sintered TIM. White spots indicate voids. 100% TIM coverage.

### B. Reliability test

For coverage inspection of the metal sheet TIM, graphite sheet TIM and Ag sintered TIM, CSAM was used to evaluate the joints. The reliability tests were performed on good units from the experiment build. Table IV provides electrical test result of each reliability test and sample size. All reliability test results met FCBGA package requirements without any electrical failures.

TABLE IV. Reliability Test Result

| Reliability items | Stress time | Metal sheet TIM **(Au BSM)** | Metal sheet TIM **(Ag BSM)** | Graphite sheet TIM | Ag sintered TIM |
|---|---|---|---|---|---|
| Precon L4 | | 0/18 | 0/18 | 0/24 | 0/24 |
| uHAST | 96 hrs | 0/6 | 0/6 | 0/8 | 0/8 |
| TC B | 1000X | 0/6 | 0/6 | 0/8 | 0/8 |
| HTS | 1000 hrs | 0/6 | 0/6 | 0/8 | 0/8 |
| Result | | Passed | Passed | Passed | Passed |

After the reliability tests, CSAM analysis was used to check for voids and delamination. In metal sheet TIM, there is no void on the die area and overflow phenomena does not propagate during the reliability test procedures. Also, there are no delaminations or joint problems between die / metal sheet TIM / lid as shown in Fig. 8. With the graphite sheet TIM, there are 10% voids and density of TIM is different from edge to center of the die in Fig. 9. Additional thermal degradation has not been observed for this graphite sheet TIM. In the Ag sintered TIM, voids were generated during reliability test with 6% voids in the die area as shown in Fig. 10.

Figure 8. CSAM image of In10Ag -TIM post reliability test (HTS 1000 hrs). White spots indicate voids and dark black indicates overflow. 100% TIM coverage with no voids.

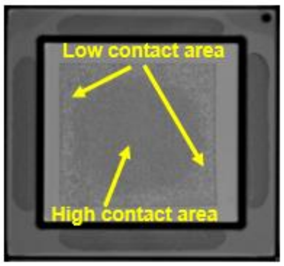



Figure 9. CSAM image of graphite sheet TIM post reliability test (HTS 1000 hrs). Dark black indicates high contact on lid. White spots indicate low contact on lid. 90% TIM coverage with 10% voids.

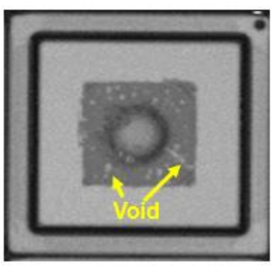



Figure 10. CSAM image of Ag sintered TIM post reliability test (HTS 1000 hrs). White spots indicate voids. 94% TIM coverage with 6% voids.

For relative adhesion analysis, the lid pull test was conducted on samples of each reliability condition of TIMs. For lid pull test, a stud jig fixture was made for the top and bottom size of PCB and shape of lid. Special high adhesion material was used and cured on the top and bottom stud to attach to the package. With an Instron machine, all prepared samples were subjected to an applied force in the vertical direction. As a result of this testing, the relative adhesion metal sheet TIM and graphite sheet TIM met the criteria of >165 kgf on 52.5-mm body size (see Fig. 11) and Ag sintered TIM met criteria > 70kgf on 45-mm body size (see Fig. 12). Au BSM treatment had greater adhesion strength than Ag BSM treatment post reliability test. Fig. 13 to Fig. 15 provide failure modes and detached shape of TIM a lid adhesive material.

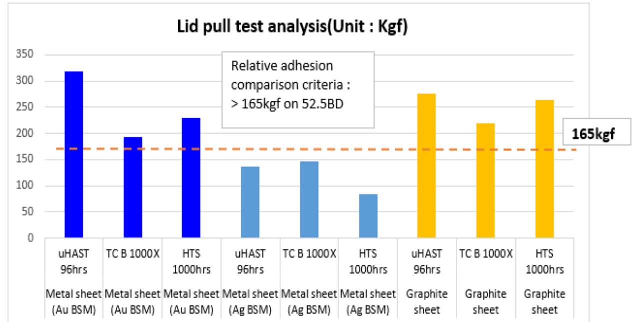



Figure 11. Lid pull test analysis post reliability test (metal TIM and graphite sheet TIM).

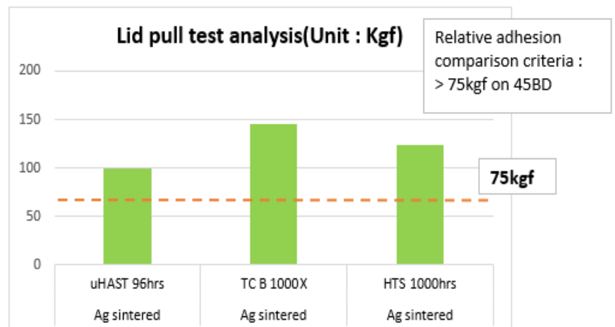



Figure 12. Lid pull test analysis after reliability test (Ag sintered TIM).

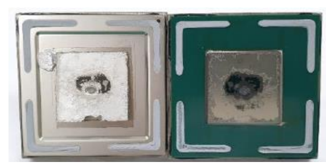


Figure 13. Lid pull test of metal sheet TIM after reliability test.

Figure 14. Lid pull test of graphite sheet TIM after reliability test.

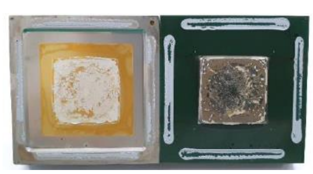


Figure 15. Lid pull test of Ag sintered TIM after reliability test.

## IV. CONCLUSION

Based on the workability and reliability tests and discussions, it has been proven that three new TIMs have advantages as high thermal interfacial materials with high bulk thermal conductivity (> 20W/mK). The metal sheet TIM (60W/mK), graphite sheet TIM (24W/mK) and Ag sintered TIM (50W/mK) will be further tested to verify that they meet FCBGA package workability and reliability requirements.

In the CSAM analysis of post reliability tests, the metal sheet TIM with 100% TIM coverage with no voids showed better performance regarding voids and delamination. The metal sheet TIM can provide a leading edge material for high power microprocessor for large body packages (> 50-mm body size) in applications such as artificial intelligence (AI), high-performance computing (HPC) and network and high-end desktop applications in preparation for the 4$^{th}$ industry revolution era.

To meet high-volume mass production, the lid attach process for metal sheet TIM is needed for automation. Since it meets the required criteria, the metal sheet TIM will be used in the near future for improved thermal or reliability performance.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