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A Hybrid Sintering Technology for High-power Density Devices Used in Aerospace Applications

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Abstract
With in-application reliability and fail-safe processes paramount, aerospace applications present unique challenges for materials suppliers. As aerospace electronic devices increase in power density to accommodate higher function, and energy-efficient, high operating temperature wide bandgap (WBG) semiconductors become more prevalent, new materials with robust thermal management capabilities and higher operating temperature ranges are required.

Recently, a hybrid technology that marries the high thermal performance of pure silver sintering materials with the reliability of epoxy-based die attach pastes has been developed and is a promising solution to address these challenges. This hybrid technology offers similar electrical and thermal performance as sintering pastes but has exhibits less voiding and is process-friendly, much like that of traditional die attach pastes. This paper presents the results of an application study aimed at developing this unique technology in the field of high-power density devices for aerospace applications.

Introduction

Breakthroughs in multiple technology frontiers have given birth to wide bandgap (WBG) semiconductors, which are transforming both commercial and defense electronics. For example, Gallium Nitride (GaN)-based high power amplifiers (HPAs) have achieved exceptional high-power densities and are increasing replacing Si-based RF power devices for radar systems [1]. InP-based material systems have demonstrated high electron mobility and peak velocity, which enables transistors with f_{max} exceeding 1THz [2]. Silicon carbide (SiC) offers high thermal conductivity and superior high temperature stability, which makes tens of kilowatt-level power switches possible [3]. New compound semiconductor (CS) integration platforms initiated by the U.S. Defense Advanced Research Projects Agency (DARPA) through Diverse Accessible Heterogeneous Integration (DAHI) program paved the way for the next generation commercial and defense systems with a goal to achieve integration complexity (number of transistors per circuit) in the order of 10^{10} while maintaining Johnson figure of merit (product of transistor cutoff frequency and breakdown voltage) above 10^3 [4]. As more and more transistors are integrated into a single chip, waste heat generated by the chip is increasing rapidly with local heat fluxes approaching several thousand W/cm^2 (chip level).

In the aerospace market, and particularly for radar applications, higher power conversion levels now require board-level assemblies and power semiconductors to cope with high current densities while ensuring effective heat dissipation in smaller package footprints. At the same time, the need to accommodate the coefficient of thermal expansion (CTE) mismatch between large dies and their substrates and assure physical integrity as well as long-term reliability further exacerbates this situation. Furthermore, WBG semiconductors can operate at significantly higher operating temperatures (~ 200 °C) [5], which traditional die attach, and packaging materials cannot withstand. The higher operating temperatures also amplify the CTE mismatch-induced thermal stress and increase delamination risk and premature failures. Effectively and safely dissipating the high heat becomes an increasingly critical and challenging task in broad adoption of these WBG devices in aerospace applications.

Thermal interface materials (TIMs) play a critical role in packaging and thermal management design for a microelectronics device. The main function of the TIMs is to thermally connect various components and allow heat to quickly and effectively dissipate from heat generating dies to ambient. The thermal resistance of the TIM is one of the key factors in determining the overall performance and reliability of electronic devices in practical applications. The reliability and instability of the performance of TIMs is a growing concern in many applications [6]. In a standard microelectronics device, there might be multiple TIMs. A TIM used to bond a die is commonly referred as TIM1. Since the TIM1 is the closest to the heat source and needs to withstand the most challenging operating conditions (the highest heat flux, the highest temperature, and the maximum temperature swings, etc.), it often represents one of the biggest thermal barriers and/or the least liable elements in the entire device. Therefore, TIM1 is one of the key components in microelectronic packaging.

The most commonly used TIM1s include solders and die attach pastes. Although solders offer good thermal performance and have traditionally been widely used in aerospace applications, their high melting points limit the application process and their mechanical stiffness poses a long-term reliability risk. Consequently, solders are increasingly being replaced by die attach pastes. Traditional die attaches pastes use high thermally conductive powders as fillers within a resin matrix. The filler particles include ceramic powders of aluminum oxide, aluminum nitride, or metal powders of silver, nickel, gold, diamond, or carbon fibers. In this system, although thermal conductivity of the filler particles is typically as high as several hundred W/m-K (i.e. 170 W/m-K for AlN, and 430 W/m-K for silver), the effective thermal conductivity of the pastes is typically less than 10 W/m-K. There are generally two reasons for this: (1) The thermal conductivity of the polymer matrix itself is inherently too low (typically around 0.2-0.3 W/m-K). It surrounds and isolates each filler particle and prevents them from effectively transferring heat. (2) Since the filler powders are typically very small, multiple particles along the heat transfer path may be required to fill and bridge a gap between two mating surfaces, which may increase the occurrence of heat transfer interruption by the low conductivity matrix.

To overcome these challenges, several new types of TIMs have been developed. The primary objective of these developments centered on replacing the randomly dispensed spherical filler particles with oriented thin wires or platelets with high aspect ratios, such as carbon fibers (CFs), carbon nanotubes (CNTs), graphite nano platelets (GNPs), and copper or silver nanowires. There have been several efforts to grow CNTs directly on substrates as TIM materials so that the CNTs are naturally aligned with the heat transfer direction. With this arrangement, Cola et. al. realized a thermal resistance of approximately 0.1 cm^2K/W under 0.7 atm pressure [7]. Compared to the 0.09 cm^2K/W that can be achieved with conventional solders in the current die attachment processes [8], this value was still too large. Studies carried out by Kim et al. [9], and Borca-Tasciuc et al. [10] verified this by showing that, although individual CNTs have high thermal conductivity, their nanocomposites with polymers have not led to the anticipated large increase in thermal conductivity. The interfacial thermal resistance between the CNT and the host matrix was found to be the main limiting factor that degraded the overall thermal conductivity of the composites. In addition, the quality of CNTs along the growth direction may be poor. For example, if amorphous regions exist, the thermal conductivity of the CNTs is adversely affected. In addition, the in-situ-grown CNT forests are costly and require high temperature processing that is typically not compatible with microelectronics packaging.

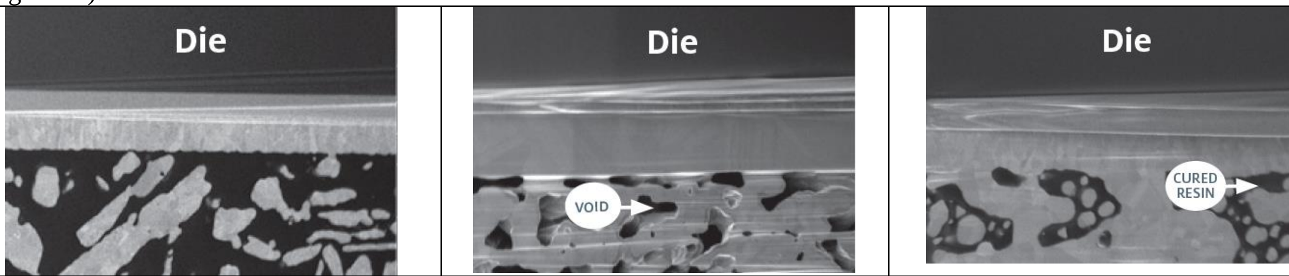
GNPs have also been studied for use as filler powders in polymer systems to improve thermal performance. However, early efforts to use conventional flexible graphite for TIM purposes have not yet led to a significant technology breakthrough. Samlc et al. [11] tested several graphite TIMs, developed by mixing exfoliated GNPs with polymeric materials and achieved thermal resistance of 0.9-1.5 cm^2K/W at a thickness of 130 μm and a pressure of 100 kPa. Fukushima, et al. [12] used exfoliated GNPs as fillers to infiltrate high density polypropylene to form high thermal conductivity nanocomposites and yielded bulk thermal conductivity of 4 W/m-K, which traditional die attach pastes can easily achieve as well. The main problem with these TIMs is that either the fillers were not aligned in the mixture or the heat transfer is perpendicular to the filler orientation, which led to tremendous reduction in heat transfer performance.

It is evident that the state-of-the-art TIMs still have not realized the full potential of the filler materials, nor do they satisfy the thermal cycling requirement in practical applications. The limiting factor is that high conductive fillers are not connected to form a continuous thermal path. Therefore, a new generation of high thermal performance, high temperature-compatible die attached and device assembly materials are required. To cope with the demand, the Microsystems Technology Office (MTO) of DARPA initiated a series of programs exploring the potential of nanomaterials and nanostructures to create high performance TIMs [13]. Advanced concepts included use of metal nanosprings, laminated solder and flexible graphite films, multiwalled carbon nanotubes (CNTs) with layered metallic bonding materials, and open-ended CNTs. The advanced research pushed scientific boundaries and showed substantial improvement from the state of the art. Although they were able to achieve thermal interface resistivities well below 10 mm^2K/W, most of these technologies are still in the conceptual stage, and substantial efforts are needed to develop the technology readiness before high volume manufacturing processes can be established.

Realizing the challenges with other approaches, a new TIM based on hybrid silver sintering-epoxy resin curing mechanisms has been developed and is presented in this paper. The technology is also commonly referred to as semi-sintering technology. The work presented here highlights the testing undertaken to evaluate the bond strength and thermal performance of the novel semi-sintering TIM.

Semi-sintering TIM

As previously indicated, the major weakness of traditional die attach pastes is that fillers are isolated inside a polymer matrix and cannot form a continuous thermal transport route through the entire bondline (Figure 1a), which drastically degrades thermal performance. Metal particle sintering (i.e. silver sintering), however, can form a well-connected structure to effectively transport heat (Figure 1b). Despite this, the sintered metal structure is typically porous and can absorb and trap moisture due to the large capillary force generated by the small pores. Therefore, in a typical application environment, and especially in aerospace applications, long-term reliability is a serious concern. Alternatively, semi-sintering is a hybrid process that marries the advantages of metal sintering with proven resin curing technologies to create a well-connected metal structure for heat transport. The resin fills and locks all pores to make the entire structure void-free and moisture-resistant (Figure 1c).



(a) raditional die attach Paste	(b) ilver sintering	(c) emi-sintering

Figure 1: Scan Electron Microscopy (SEM) images of different TIM1s [14].

The traditional sintering process typically requires a sintering temperature close to that of the metal melting point, but this temperature generally cannot be tolerated by typical microelectronics devices. The semi-sintering die attach paste uses specially selected, very fine silver particles which can achieve silver sintering at a temperature as low as 175° C. The bonding strength of a semi-sintered bondline is primarily provided by the sintered silver structure, as opposed to the cured resin matrix. Re-melting silver would require an extremely high temperature, since the melting point of silver is above 1000º C. This unique feature makes the semi-sintered bondline resistant to very high operating temperatures and delivers excellent creep resistance.
In addition, the porous metal structure offers a significantly lower modulus as compared to solid metal, which makes it a potential solution for assemblies with large CTE mismatch components. In addition, the higher thermal performance of semi-sintering allows to thicker bondlines to further reduce CTE mismatch-induced thermal stress.

The semi-sintering die attach paste can be applied via standard stencil or screen printing, dispensing and/or pin transfer, which makes it compatible with most standard assembly processes and equipment.

Material Properties
Key properties of the semi-sintering die attach paste are shown in Table 1. To demonstrate the performance advantages and unique application features of the semi-sintering paste, a widely used die attach epoxy paste was chosen as control and its key properties are also shown in Table 1. Compared to the epoxy paste, the semi-sintering paste offers much higher thermal and electrical conductivities and significantly lower CTEs, which makes it a potential candidate for aerospace and defense applications.

It should be noted that higher bulk material thermal conductivity does not necessarily equate to good thermal performance in application because interfacial thermal resistance between the TIM and surface might play a significant role -- especially when the TIM doesn't have good compliance to the surface. Therefore, good thermal performance of the semi-sintering TIM needs to be validated by experiments.

Table 1: Key properties of the TIMs

	Control	Semi-sintering
Technology	Die attach paste	Semi-sintering paste
Chemistry	Epoxy	Epoxy
Filler type	Silver	Silver
Bulk Thermal Conductivity (W/mK)	3.2	100
Volume Resistivity (Ohm·cm)	0.0005	7×10^{-6}
Cure	30 min @ 150 ºC	20min ramp to 130ºC, hold 2h; 15min ramp to 200ºC, hold 2h.
Tg by TMA	90 ºC	25 ºC
CTE1 (ppm/ºC)	55	25
CTE2 (ppm/ºC)	200	103

Modulus @25ºC (GPa)	7.8	12.5

Experiments

Outgassing Test

Aerospace applications have higher standards in restricting volatile contents inside a material. To be qualified for aerospace applications, the semi-sintering paste must meet NASA's criteria on outgassing.

Therefore, outgassing tests were conducted based on ASTM E595-15 standards [15]. The tests were performed in a vacuum environment of less than $5x10^{-5}$ torr for a duration of 24 hrs. at 125º C. Total mass loss (TML), collected volatile condensable materials (CVCM), and the amount of water vapor recovered (WVR) were measured and results are shown in Table 2. Historically, a TML of 1% and CVCM of 0.1% have been used by NASA as screening standards for rejection of spacecraft materials. The outgassing tests indicated that the semi-sintering paste met NASA outgassing standards.

Table 2: Outgassing test results

	Semi-sintering Paste	NASA criteria	Comments
TML	0.2%	<1%	Pass
CVCM	0.02%	<0.1%	Pass
WVR	0.03%	-	

Bond Strength

For a die attach paste, ensuring good and reliable bonding strength is a key requirement. Previous analysis indicates that that surface metallization and curing schedule are among the critical factors governing bond strength quality in a metal sintering process. In aerospace applications, copper tungsten (CuW), copper molly (CuM) and kovar are commonly used substrates/carriers for high power RF devices -- primarily because their CTEs are quite close to that of typical semiconductor materials.

For this study, to mimic practical packaging systems in aerospace devices, copper tungsten (CuW) thin sheets with a composition of 30% Cu and 70% W were used. The CuW substrates measured 25 mm x 50 mm x 1 mm. Dies used in this study were Si dies measuring 2 mm x 2 mm. Since the semi-sintering paste is silver-based, silver or gold surface metallizations were expected to offer better sintering quality than bare CuW. Therefore, a CuW substrate was plated with a 1 micro thick silver metallization. 24 Si dies with silver backside metallization were attached on the CuW substrates with and without the silver metallization. Curing schedules were based on the recommended values listed in Table 1. Die shear tests were performed before and after a 140-cycle thermal shock between -55º C to 150º C.

Table 3 presents the die shear test results. For reference, a typical acceptable die shear strength for a 2 mm x 2 mm die is around 5 kg. This test indicated that the semi-sintering paste offers excellent bonding strength for attaching dies on either bare CuW or CuW substrates with silver metallization. An interesting phenomenon was identified in the 140-cycle thermal shock test. Die shear strength for the bare CuW reduced after the thermal shock test, while it increased for the CuW with silver metallization. An explanation might be related to the fact that extended time at high temperature tends to strengthen metal sintered connections and improve sintering quality. The dominant bonding mechanism for the CuW with silver metallization may be the silver sintering, indicating that thermal shock could improve bonding strength. However, the dominant bonding mechanism for the bare CuW may be epoxy bonding, where thermal shock negatively impacted the bonding strength. The test results suggest that silver metallization on CuW substrates is preferred.

Table 3: Room temperature die shear test results

	Initial		After 140-cycle thermal shock	
Samples	Bare CuW	CuW with Ag metallization	Bare CuW	CuW with Ag metallization
units	Kg	kg	kg	kg
1	14.749	12.134	12.712	15.723
2	13.561	13.241	12.003	15.656
3	15.381	13.269	12.182	11.705
4	13.534	13.226	9.847	17.596
5	13.638	13.577	13.29	15.207
6	13.386	12.059	-	-

Mean	14.042	12.918	12.007	15.177

Thermal Performance

Die shear tests demonstrated that the semi-sintering paste offers excellent bonding strength to CuW substrates. However, to ensure that the semi-sintering material can be used in aerospace applications, proof of high thermal performance in a package is required. In addition, thermal performance is a good indicator of sintering quality since good sintering tends to form larger and stronger silver particle interconnections. To verify the hypothesis that semi-sintering quality is improved with longer time at high temperatures, a series of tests was organized to analyze the impact of sintering time on thermal performance.

Netzsch laser flash LFA 467 equipment was used to evaluate in-package thermal performance of the semi-sintering paste. The test method was based on three-layer laser flash principles. Gold-plated copper disks with a diameter of 12.7 mm and a thickness of 0.45 mm were fabricated for building the test specimen. The semi-sintering paste was used to bond a pair of the disks together. 100 µm thick spacers were used during the bonding process to ensure a controllable and uniform bondline thickness. Upon curing each test specimen, X-ray microscopy was used to examine the bondline and screen test specimen. Figure 2 shows two sample X-Ray images of the test specimen along with a specially created reference sample with entrapped air pockets in the bondline. It's clear that the X-ray is capable of providing an accurate assessment on the bondline to screen test the specimen prior to performing the laser flash tests.

(a) Semi-sintering TIM	(b) Control paste	(c) Reference sample

Figure 2: Sample X-Ray images of test specimen

Figure 3 illustrates the thermal diffusivity of the semi-sintering bondline as a function of sintering time. The effective thermal conductivity of the sintered bondline as a function of sintering time can be seen in Figure 4. It is evident that extending sintering time can significantly improve the thermal performance of semi-sintering for the present package design. Also, semi-sintering resulted in significantly higher thermal performance than the control die attach paste. Additional laser flash tests were also conducted with a test specimen built with a high-performance silver-tin solder (thermal conductivity around 33 W/m-K). The test results suggest that the semi-sintering TIM offers better in-package thermal performance than the Ag-tin solder.

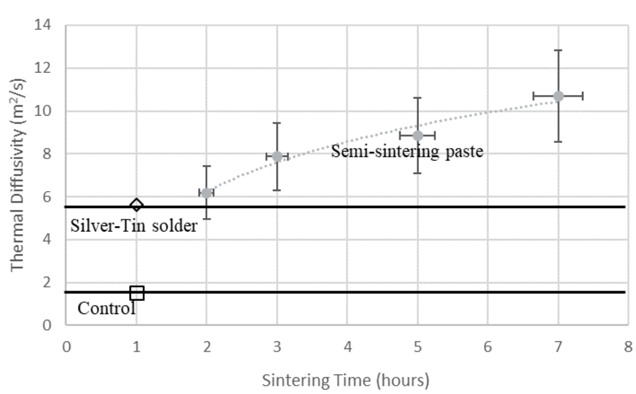


Figure 3: Thermal diffusivity of the bondline

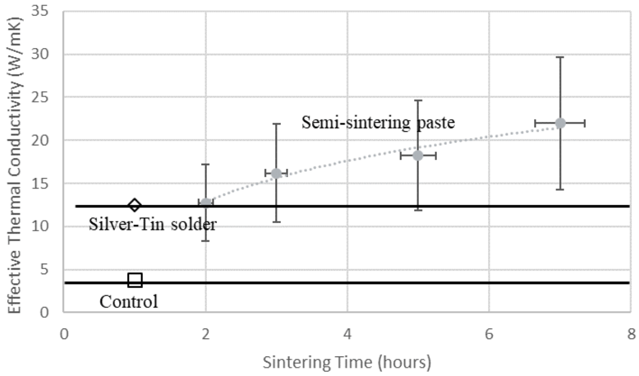


Figure 4: Effective thermal conductivity of the bondline

A comparison of two different sintered bondlines is shown in Figure 5. The thicker bondline demonstrated significantly lower effective thermal conductivity and extending sintering time did not enhance the thermal performance as much as it did with the thin bondline. This may indicate that the bondline thickness of the semi-sintering paste cannot be too thick. Otherwise, the sintering quality/thermal performance will suffer.

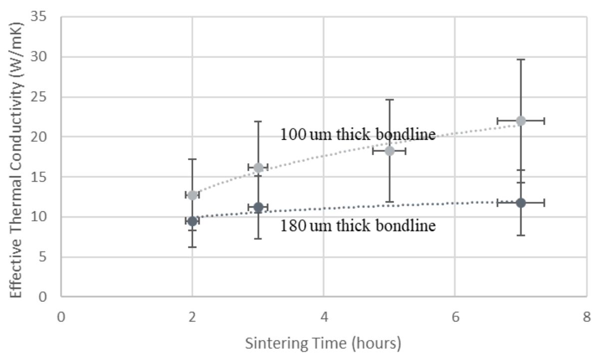
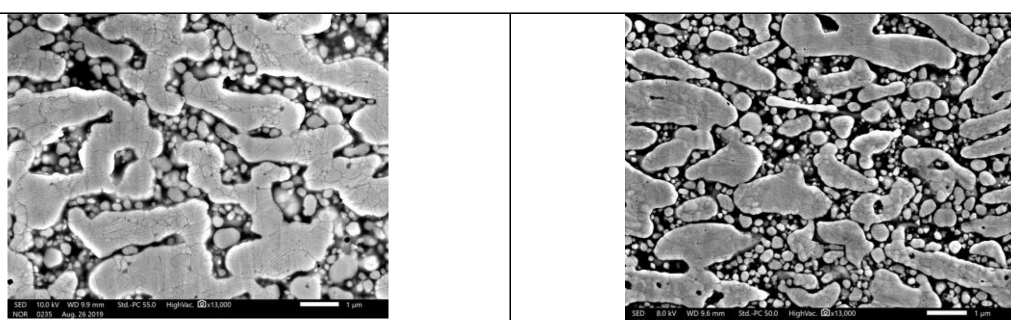


Figure 5: Impact of sintered bondline thickness on effective thermal conductivities.

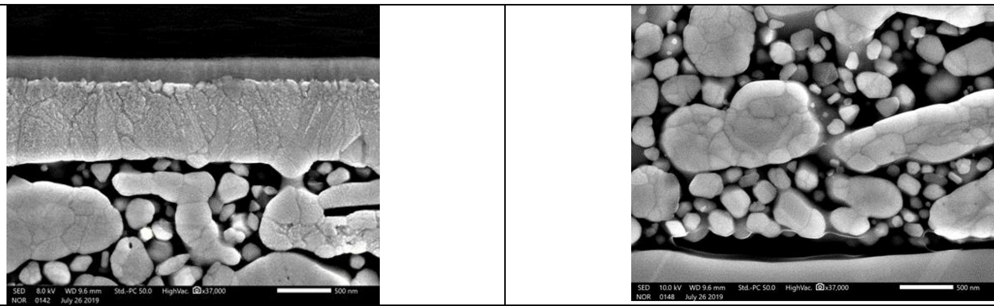
To better understand the sintering process and quality, scan electron microscopy (SEM) was used to examine sintered bondlines of microelectronics devices built with 2 mm x 2 mm Si dies on standard silver lead frames (LFs). Figure 6 shows images of sintered silver structures at different sintering conditions. The study showed that a higher sintering temperature can significantly augment silver particle interconnections and thereby result in higher thermal transport. This can also be used to explain the previous finding that longer sintering time improves thermal performance.



(a) Sintering at 200° C for 2 hrs.	(b) Sintering at 175° C for 2 hrs.

Figure 6: SEM images of sintered bondlines

The interface between the semi-sintered bondline and surfaces of the die and the lead frame are illustrated in Figure 7. Compared with images in Figure 6, the sintered metal connections between the silver particles and the surfaces were inferior to the particle interconnections in the bulk sintered material. This was especially evident on the lead frames; the silver particles were not even connected to the lead frame surface, where a large interfacial thermal resistance was expected. This might explain that, although bulk thermal conductivity of the semi-sintering material is close to 100 W/m-K, its in-package effective thermal conductivity was less than 30 W/m-K. The data suggests that the primary cause for this is the poor sintering quality between the silver particles and surface.



(a) Die side	(b) Lead Frame Side

Figure 7: SEM images of interface between semi-sintering material and surfaces of components

Although the semi-sintering paste has not realized its full potential in practical applications, it nevertheless provides some of the best thermal performance as compared to traditional TIMs. Figure 8 shows thermal resistivity of the sintered bondline. For the current package design, the commercially available semi-sintering TIM with an optimized curing schedule can deliver a thermal resistance close to 0.05 Kcm^2/W, which is approaching the performance achieved by several of DARPA NTI projects referenced in the introduction.

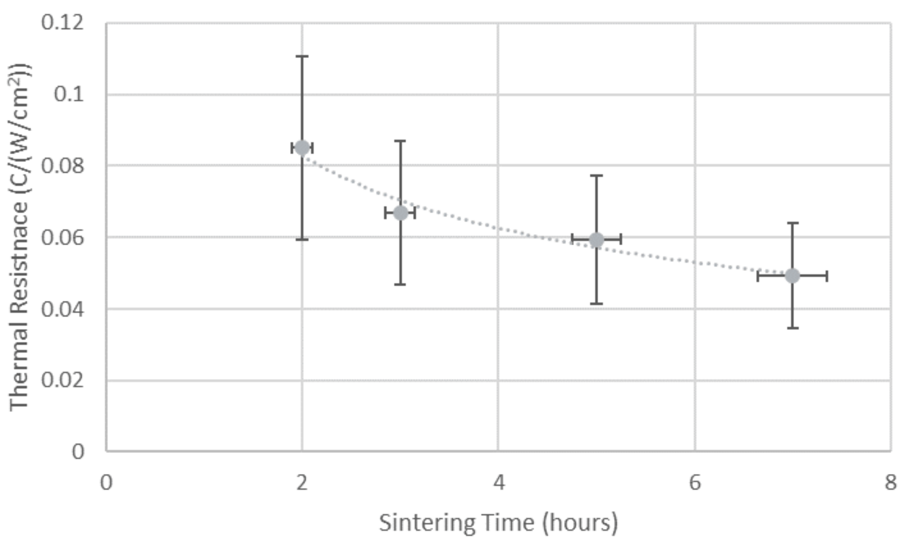


Figure 8: Thermal resistance of the sintered bondline

Conclusions

Comprehensive experimental tests have been conducted to evaluate the bonding strength and thermal performance of semi-sintering die attach paste. The test results indicate that the semi-sintering TIM can maintain high bond strength and deliver ultra-high thermal performance which exceeds that of traditional die attach pastes and solders. SEM studies indicated that sintering quality was poor between the silver particles and component surfaces. Further development may need to focus on the interface between the component surfaces and silver particles.

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