A Hybrid Pressure-less Silver Sintering Technology for High-power Density Electronics

Yuan Zhao, Bruno Tolla, Doug Katze, Glenda Castaneda, John Wood, Jo-Anne Wilson and David Brand
Henkel Corporation
14000 Jamboree
Irvine, CA92606, USA
Ph: 949-293-5116
Email: yuan-david.zhao@henkel.com

Abstract
Integration of smaller, higher-functioning devices and use of advanced high thermal chip structures present thermal management challenges in the aerospace sector where reliability is the top priority and fail-safe processes/materials are the standard. As power density increases rapidly, traditional die attaching technology is becoming an increasingly limiting factor in microelectronics packaging for the next generation aerospace and defense systems. This paper introduces an advanced hybrid silver sintering technology, which incorporates ultra-high thermal and electrical performance of silver sintering with high reliability and process friendly of epoxy-based die attach technology. Unlike traditional silver sintering that requires high temperature and pressure, this hybrid sintering paste can be processed without applying any pressures in temperature ranges that are normal in microelectronics packaging processes. This paper presents results of an application study aimed at developing this unique technology in the field of high-power density devices for aerospace applications.

Key words
RF power devices, thermal management, chip-scale cooling, adhesives, and RF grounding

I. Introduction
Advancements in multiple technology frontiers, including electronics design, material science, thermal management, and manufacturing technologies, have given birth to wide bandgap (WBG) semiconductors, which are transforming both defense and commercial electronics. For example, Gallium Nitride (GaN)-based high power amplifiers (HPAs) have demonstrated drastically increased breakdown voltage, higher efficiency, and smaller footprint, which leads to exceptional high-power densities. These devices offer broadband performance with higher drain efficiency than Silicon (Si)- based or vacuum electron devices based solid state power amplifiers. They are increasing replacing Si-based radio frequency (RF) power devices for radar systems [1]. Indium phosphide (InP)-based material systems have demonstrated high electron mobility and peak velocity, which enables transistors with f\text{max} exceeding 1TeraHz [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 defense and commercial 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/cm² (chip level).

In the aerospace and defense systems, 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 defense and aerospace applications. Die attaching technology plays a critical role in packaging and thermal management design for a microelectronics device. The main function of the die attaching is to bond the die onto its substrate/carrier and allow heat to dissipate from heat generating dies quickly and effectively to ambient. Since the die attach 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, die attach is one of the key components in microelectronic packaging. In addition, many advanced high-power electronics devices are vertical in electrical and thermal management design. So device assembly, especially die-attach in the power devices, need to be both an electrical interconnection and thermal path, as opposed to only a thermal pathway as in traditional microelectronic device packaging. The die attach also needs to provide a reliable mechanical bond to a substrate, which provides electrical insulation required for mounting the device on or cold plate. Traditionally, electrically conductive die attach materials have primarily included solders and electrically conductive die attaching adhesives. Although solders offer good thermal performance and have traditionally been widely used in aerospace applications, their high melting points limit the application processes. Their mechanical stiffness and creep problem poses a long-term reliability risk. Consequently, solders are increasingly being replaced by electrically conductive adhesives (ECAs).

ECA is a curable or thermoset material and typically consists of a polymeric resin, a hardener and conductive fillers. The curing (or thermosetting) process is a non-reversible process unlike solder reflow, which enables lower process temperature but higher operation temperatures. This process-friendly feature not only drastically extends application of the ECAs to new areas beyond traditional solder’s territories, but also significantly improves creep resistance at bonding area and thus enhance device reliability. The polymeric resins typically include epoxy, acrylic, and silicone, etc. Epoxy offers excellent mechanical bonding performance and high thermal/chemical stability, which make it a workhorse in the adhesive family. The main weaknesses of the epoxy typically include higher curing temperature and longer curing time. Acrylic offers an alternative solution to offset these weaknesses. Acrylic allows fast curing (snap curing) at lower (or ambient) temperatures for high throughput applications. But its high temperature stability is poor. Silicone offers excellent high temperature stability as well as improved ability in handling CTE mismatched assemblies. But its bonding strength is typically orders of magnitude lower than epoxy or acrylic. Epoxy hardener systems include anhydride, imidazole, amine, peroxide, and others. The most used conductive filler is silver filler (including flakes or spheric particles or mixture of the two). Others include gold, nickel, carbon, or silver-plated copper powders, etc. Traditional technology in making ECAs is to dispense/suspend the conductive fillers in a polymeric resin matrix, which forms point contact between the fillers to conduct electrical current and heat. With this approach, although thermal conductivity of the filler particles is typically as high as several hundred W/mK (i.e. 430 W/mK for silver), the effective thermal conductivity of the ECAs is typically less than 10 W/mK. There are two reasons for this: (1) The thermal conductivity of the polymer matrix itself is inherently too low (typically around 0.2-0.3 W/mK). It surrounds and isolates each filler particle and prevents them from effectively transferring heat or electrical current. (2) Since the filler powders are typically very small, multiple particles 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, many studies have been conducted and multiple new technologies have been developed [6]. The primary objective of these developments centered on replacing the randomly dispensed 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 thermal interface 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 cm²K/W under 0.7 atm pressure [7]. Compared to the 0.09 cm²K/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 have not yet led to a significant technology breakthrough. Samle et al. [11] tested several graphite thermal interface materials, developed by mixing exfoliated GNPs with polymeric materials and achieved thermal resistance of 0.9-1.5 cm²K/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 Microsystems Technology Office (MTO) of DARPA initiated a series of programs exploring the potential of nanomaterials and nanostructures to create high performance thermal interface materials. Bar-Cohen, et. al. [13] conducted a critical review about multiple advanced concepts included use of metal nanosprings, laminated solder and flexible graphite films, multwalled 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 mm²K/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.

It is evident that the state-of-the-art filler/resin mixing technologies 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 and electrical path. Therefore, a new generation of high performance and high reliability die attach and device assembly materials are required. Realizing the challenges with other approaches, a new ECA 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, electrical and thermal performance of the novel semi-sintering ECA.

II. Semi-sintering Adhesive

As previously indicated, the major weakness of traditional ECAs is that fillers are isolated inside a polymer matrix and cannot form an efficient thermal and electrical transport route across the bondline (Fig. 1a), which drastically degrades thermal and electrical performance. Metal particle sintering (i.e. silver sintering), however, can form a well-connected metal structure to effectively transport heat (Fig. 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 silver 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 (Fig. 1c).

![Fig. 1: Scan Electron Microscopy (SEM) images of different technologies](image)

The traditional sintering process typically requires a sintering temperature close to that of the metal melting point, but this temperature cannot be tolerated by typical microelectronics devices. For example, melting point of silver is around 1000 °C, which is significantly beyond tolerance of most microelectronics devices. In defense and aerospace systems, most die attaching applications prefer process temperature around 150 °C or below. So, reducing silver sintering temperature below 150 °C is one of the key requirements from the industries.

A novel die attach adhesive was developed with specially selected and very fine silver particles, which makes low temperature sintering feasible. The semi-sintering ECA 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. A preliminary study of the semi-sintering paste cured at 200 °C was presented in 2020 [15]. This paper is focused on developing a curing schedule at 150 °C and demonstrating its performance.

III. Experimental Studies

A preliminary SEM study was conducted to assess/evaluate feasibility of the adhesive sintering at 150 °C. Fig. 2 shows a top view of the new adhesive at different stages. Fig. 2a shows the SEM image of the adhesive prior to sintering. The silver flakes appeared piled up and aligned horizontally. Fig. 2b shows the state of the adhesive after sintering for 2 hours at 150 °C. The SEM image was like Fig. 2a, which suggested that silver fillers were not sintered together. However, Fig. 2c presented a vastly different structure characteristic from the previous two. The silver flakes disappeared, and a porous structure was shown up, which suggested that the silver sintering was achieved.
Fig. 2: SEM images at sintering temperature of 150 °C.

Fig. 3 shows a similar study for sintering temperature at 200 °C. Fig. 3a showed state prior to sintering, which is identical to Fig 2a. However, after sintering for 2 hours at 200 °C (Fig. 2b), a porous structure identical to Fig 2c appeared, which indicated successfully silver sintering. Fig. 3c showed a similar porous structure after sintering at 200 °C for 6 hours.

Combining with Fig 2, it indicated that the silver sintering could happen after 6 hours at 150 °C or 2 hours at 200 °C. To verify the SEM findings and demonstrate advantages of semi-sintering over traditional ECAs, series of experiments were conducted.

As indicated in previous sections, adhesives based on sintering technology are expected to deliver significantly enhanced electrical and thermal performance over traditional ECAs. Volume resistivity (VR) is a good indicator of electrical conductivity and thus sintering quality.

Heat transfer in solids is due to the combination of lattice vibrations of the molecules and the energy transport by free flow electrons [16]. In metals, heat conduction occurs mainly by the movement of free electrons inside the metal atoms. This is the reason for why good electric conductors are also good thermal conductors. So, the VR is also a good indicator for heat transfer performance in a silver sintered structure.

A volume resistivity test system was built by using a polycarbonate block (Fig. 4). Four spring loaded leads were inserted in drilled holes inside the block. The two inner leads with a space of 50 mm are for voltage measurement while the two outer leads provide a DC current to flow through a test sample. An Agilent multimeter (Model 34401A) was used to measure the current and the voltage.

Fig. 4: Schematic of volume resistivity test system

A test specimen was made by coating a 1 mm thick glass slide with a test adhesive (Fig. 5). The coated area had a width of 5 mm and length of 150 mm. Typical coating thicknesses range from 50 micron to 150 micron. Then, the test specimen was placed in a box oven to cure in accordance with designed curing schedules.

Fig. 5: Schematic of a test specimen (top view of glass slide)

After curing, the test specimen was placed on top of the volume resistivity test system with the coated area touching the spring-loaded leads and press them halfway down. Then, current and voltage were recorded. Volume resistivity of the test ECA is calculated by (1).

\[
VR = \frac{V \times (w \times t)}{I \times l}
\]

where:
- \(VR\) = volume resistivity, ohm-cm
- \(V\) = voltage, V
- \(I\) = current, A
- \(w\) = width of the coated section, cm
- \(t\) = thickness of the coated section, cm
- \(l\) = length between the two inner leads, cm

Fig. 6 showed volume resistivity test results of the new adhesive sintering at 150 °C for different periods. VR was around 0.07 ohm-cm when the ECA sintering for 2 hours, which suggests poor or no sintering between particles since traditional ECAs can also achieve this level. However, after sintering for 6 hours, the VRs dropped significantly and were...
below $2 \times 10^{-5}$ ohm-cm, which approached the VR results of the adhesive sintering at 200 °C for more than 2 hours (blue area in Fig. 6). This proved that silver sintering was achieved when sintering at 150 °C for more than 6 hours. These results were consistent with the findings of the SEM study (Fig. 2).

As indicated before, bonding strength of a semi-sintered adhesive is provided by combination of cured resin matrix and sintered silver structure. So bonding strength is expected to increase when silver sintering is achieved. A die shear study was conducted with a Dage 4000 die shear tester (Fig. 7). Schematic of the die shear system is shown in Fig. 8.

Fig. 6: VR of the new ECA sintering @150 °C

Fig. 7: Dage 4000 Die shear tester

Fig. 8: Schematic of die shear tester

Fig. 9 presents die shear test results. It clearly showed that, sintering for more than 6 hours at 150 °C could increase die shear strength significantly, which reinforces the previous conclusions of successfully silver sintering after 6 hours at 150 °C.

Table 1: Key properties of the two ECAs

<table>
<thead>
<tr>
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<th>Control</th>
<th>Semi-sintering</th>
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<tbody>
<tr>
<td>Technology</td>
<td>Die attach paste</td>
<td>Semi-sintering paste</td>
</tr>
<tr>
<td>Chemistry</td>
<td>Epoxy</td>
<td>Epoxy</td>
</tr>
<tr>
<td>Filler type</td>
<td>Silver</td>
<td>Silver</td>
</tr>
<tr>
<td>Volume Resistivity (Ohm·cm)</td>
<td>0.0005</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td>Cure</td>
<td>60 min @ 150 °C</td>
<td>6 hours at 150 °C</td>
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Netzsch laser flash LFA 467 equipment was used to evaluate in-package thermal performance of the semi-sintering adhesive. 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 0.5 mm were fabricated for building the test specimen. The test pastes were 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.

Fig. 9 Room temperature die shear strength of the new ECA sintering @150 °C

The previous studies successfully demonstrated that the new semi-sintering paste could achieve silver sintering at 150 °C after sintering for more than 6 hours. However, to ensure that the semi-sintering adhesive can be used in aerospace applications, proof of high thermal performance in a package is required.

To demonstrate the performance advantages of the semi-sintering paste, a widely used die attach epoxy paste was chosen as control. Key properties of the two pastes are shown in Table 1.

Fig. 10: Tri-layer test specimen for laser flash tests
Upon curing each test specimen, X-ray microscopy was used to examine the bondline and screen test specimen. Fig. 11 shows X-Ray images of four test specimens. Among them, one showed significant air entrapment or cracking problems. This study indicates that the X-ray can conduct quality check when the paste adhesives are used in applications.

Laser flash tests on the tri-layer test specimen were conducted and results are shown in Table 2. Thermal conductivity of the new semi-sintering ECA was around 20 W/mK while the control material was around 3.4 W/mK, which indicates that the new semi-sintering ECA offers 6 times enhancement on thermal performance comparing with the traditional ECA.

![Fig. 11: X-Ray images of test specimen sintering at 150 °C for 6 hours.](image)

### Table 2: Thermal conductivity test results

<table>
<thead>
<tr>
<th>Samples</th>
<th>Thermal Conductivity (W/mK)</th>
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<tbody>
<tr>
<td>Control</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.3</td>
</tr>
<tr>
<td>2</td>
<td>3.8</td>
</tr>
<tr>
<td>3</td>
<td>3.2</td>
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<tr>
<td>Semi-sintering</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
</tr>
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</table>

### IV. Conclusion

Comprehensive experimental tests have been conducted to evaluate performances of a new semi-sintering ECA. The test results indicated that the new adhesive could achieve silver sintering at 150 °C after sintering for 6 hours, which meets typical requirements of microelectronics assembly processes. The hybrid silver sintering paste achieved an effective thermal conductivity around 20 W/mK, which significantly outperformed the traditional ECA in thermal performance. This demonstrates that the semi-sintering product has enormous potential for high power density electronics applications.

### Acknowledgment

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### References


[3] Cree’s Silicon Carbide Schottky Diode Chip CPW2-1200-S050B.


