Enhancing Semiconductor Package Reliability through Mechanical Property Optimization of Pressureless Sintering Die Attach Adhesives

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Abstract

There is growing demand for high-power devices, wide bandgap SiC and GaN semiconductor materials in semiconductor market, and a drive to integrate die attach materials that can replace lead-containing solders. However, epoxy-based and solder materials face challenges to meet high thermal conductivity and survive elevated working temperatures. Pressure-assisted silver sintering has overcome these challenges, but the downsides of pressure-assisted silver sintering are that it requires special equipment and for some applications, packages are unable to withstand the pressure required to facilitate sintering.

Pressureless sintering materials could be processed using the same equipment as traditional die attach adhesives. They develop strong metal bonds to substrates, providing high thermal conductivity and withstanding high temperatures. However, compared to pressure-assisted sintering, pressureless materials may have difficulties to form a dense bondline structure if the formulation design is not optimized. Moreover, once the sintered structure is built during cure, further bondline reduction may induce additional stress. Therefore, it is critical that the pressureless sintering material's mechanical properties are formulated to effectively manage stress and pass all reliability testing – especially for automotive packages.

This paper will present the findings from a study that evaluated the impact of various formulation components – such as silver packing and resin chemistry – on the mechanical properties and interfacial bonding of pressureless sintering die attach adhesives. The effect on in-package reliability performance was also investigated to better understand material properties that can pass reliability testing while maintaining high thermal and electrical conductivity adhesive requirements.

Key words

Automotive reliability, die attach adhesives, pressureless silver sintering, semiconductor packaging

I. Introduction

The emerging technology trends of high-power electronics and high-performance electric vehicles are pushing semiconductor industries to generate highly functional chip-based innovative materials. Wide bandgap SiC and GaN semiconductor materials offer a foundation for the development of high-power devices with high efficiency and advanced thermal dissipation. The excellent electrical and physical properties of SiC and GaN allow semiconductor power devices to operate at high voltage, high temperature, and high frequency that enable efficient power switching and reduced power loss [1]. Advanced technologies are required to allow the full exploration of the capability of new semiconductors.

The applications of these improved semiconductors strongly depend on the evolution of package manufacturing. Packaging improvement is also needed to withstand the strict requirements in terms of performance, efficiency, and durability [2]. For some special applications, e.g. aircraft and space exploration craft, the operating temperature is up to 300 °C or even higher. Currently, solder for new automotive power modules is made of tin-based compounds [3,4]. Because of its low melting temperature and degradation, tin-based solder is not suitable for supporting temperatures higher than 150 °C [5]. A replacement of such technology is urgently required to improve performance and reliability over the current solder process.

The traditional resin-based die-attach paste cannot overcome the high thermal conductivity requirements. In recent years, many studies have shown the bright prospects of silver paste sintering technology in die bonding of power devices to metalized substrates in the power module packaging [6,7]. High melting point, as well as excellent thermal and electrical conductivities of sintered bulk Ag, significantly improve die-attach performance and reliability for high-temperature operation. Also, silver sintering materials do not contain hazardous substances such as lead and cadmium.

One of the major drivers for the sintering process is the change in free energy within the silver sintering product. As the silver remains in the solid state during the mass transport process, silver particles are fused both to each other and to the metallization of die and substrates. Micron silver flakes and silver nanoparticles have more free energy and need less external energy to initiate the fusion process allowing die-attach material sinter at a low temperature of <200 °C [8]. Die attachment by silver sintering at such low temperatures could relieve residual thermal mechanical stress and avoid chip damage [9].

Besides the particle size, there are two main factors that impact the sintering diffusion rate and sintering process: the sintering temperature and the mechanical pressure applied to the particles. Pressure-assisted sintering forces the particles into contact and improves the diffusion mechanisms forming dense sintered joints. However, most of the bonding equipment currently in use is designed for soldering and does not allow applying any pressure on the parts. Therefore, there is a strong need to use pressureless sintering processes [10]. For pressureless sintering, effectively managing stress is critical to passing all reliability because additional stress may be accumulated due to continual sintering and further bondline reduction.

This paper will present the impact of various formulation components, such as resin chemistry, silver loading, and silver packaging, on the mechanical properties and material reliability performance. Reliability appears to improve as adhesion strength, thermal conductivity, and strain/stress at break are increased, which indicates a promoted sintering on both interfacial bonding and the bulk of the die attach bondline. The effect on in-package reliability performance was also investigated to better understand material properties that can pass reliability testing while maintaining high thermal and electrical conductivity and adhesive requirements.

II. Materials and methods

A. Materials

The formulations presented here are a mixture of silvers, resins, curatives, and additives from various commercial vendors. The mixtures were dispersed with processing that utilized planetary mixers and 3-roll mills.

These formulations are then used to bond 380 µm thick, Ag back side metalized, dummy Si die to either bare Cu or Ag plated QFN lead frames.

B. Adhesion

Die shear specimens were built using a Datacon EVO gen 3 die bonder with the build criteria of full die coverage, 50% fillet height, and a target wet bondline of ~30 µm. The die shear specimens were then cured in ovens with running nitrogen, maintaining oxygen levels under 20 ppm. Temperatures were maintained at 200 °C or 220 °C for 1 hour to ensure sintering of silver in the pastes. Hot die shear testing was performed on these cured parts using a Nordson DAGE 4000PLUS BondTester with the sample stage heated to 260 °C. At least 6 replicate tests were performed for each set of material specimens.

C. Conductivity

Electrical conductivity was measured using a 4-point probe resistivity test method in accordance with ASTM D2739. Test specimens were generated by casting thin strips of standardized width and thickness on glass slides. These specimens were then cured as described above and volume resistivity was measured. At least 3 replicate tests were performed for each material.

Thermal conductivity was measured using a laser-flash measurement method in accordance with ASTM E1461. Samples were casted on PTFE surfaces with thicknesses of ca. 500 µm. These samples were cured as described above and 0.5-inch diameter circles were punched out of the casted film. Cured material density was measured with a balance and input for thermal conductivity calculation of each material. Measurements were done using a NETZSCH Laser Flash Analyzer with at least 2 replicates for each material.

D. Mechanical Properties

Modulus at various temperatures was measured with a dynamic mechanical analysis in accordance with ASTM D5026. Films of ca. 200 µm thickness were casted on PTFE and cured as described above. 8 mm wide test specimens were punched from these films and tested using a film tension clamp on a TA DMA Q800 instrument. Measurement parameters are 5 µm amplitude for a 25 mm clamp distance at a frequency of 10 Hz over a ramp rate of 5 °C/min.

Strain and stress at break were determined by tensile testing in accordance with ASTM D638. Films of ca. 300 µm thickness were casted on PTFE and cured as described above. Type V (ASTM D638) dog-bones were punched from these films, and they were tested on an Instron Universal Testing System using pneumatic grips. Tests were performed at room temperature with a crosshead speed of 0.5 mm/min. At least 3 replicates were tested for each material.

E. Reliability

Reliability samples were bonded similarly to the adhesion specimens with the same overall die attach targets. Following the initial die attach cure, samples were over-molded, post-mold cured, and singulated. Baseline T0 data was gathered in the form of acoustic imaging on a Sonix Echo-VS. Representative parts were selected for ion-milling on the Hitachi ArBlade5000 followed by SEM imaging using Jeol JSM-IT500. Samples then underwent moisture sensitivity level 3 testing in accordance with JEDEC Standard J-STD-020 and finally thermal cycling 2 cy/hr from 155 °C to -65 °C over 1000 total cycles. Acoustic and SEM imaging were repeated post MSL and post TC.

III. Results and Discussion

A. Formulation Design

Table I. Formulation Design

	FOR1	FOR2	FOR3	FOR4	FOR5
Resin Chemistry	RH1	RH1	RH1	RH2	RH1
Ag Package	Ag1	Ag2	Ag2	Ag2	Ag3
Ag Loading	L1	L2	L3	L3	L4

Pressureless sintering die attach pastes were designed to achieve better sintering by adjusting key formulation aspects such as resin chemistry, Ag package, and Ag loading. The formulations investigated in the studies are summarized in Table I. For resin chemistries, RH1 and RH2 describe two different base resin chemistries (i.e., acrylate, epoxy, hybrid, etc.). Different silver packages were studied to achieve metallic bonding on the substrate and die interfaces after the pressureless sintering process. These different silver packages utilize combinations of different silvers of various sizes, shapes, surface chemistry, types, and compositions. The relative ratios of these silver combinations were then balanced to optimize packing for sintering but minimize post-cure defects. Finally, these formulations contain both resin and silver and the relative amounts of silver vs resin is critical for not only achieving pressureless sintering, but also balancing internal stresses within the bondline. Several silver loading levels were investigated where L1<L2<L3.

Majority of these formulations are designed with stepwise changes in mind. Comparing FOR2 to FOR3 shows the impact of varying Ag loading while holding resin type and Ag package constant. Comparing FOR3 to FOR4 will highlight the impact of resin chemistry while maintaining Ag package and Ag loading. FOR1 and FOR2 do have variation in both Ag package and loading which is necessary to allow Ag1 package type to successfully sinter. Similarly, the FOR5 formulation has needed changes in both Ag package and Ag loading. FOR5 is special, however; while FOR1-4 are designed for sintering to silver metalized substrates, FOR5 is a complete change in silver package and loading to target interfacial sintering on copper surfaces, which poses additional challenges. To achieve sintering on Cu surfaces, sintering driving force and silver packages needs to be carefully designed to support Ag-Cu bonding.

B. Adhesion

To achieve sufficient adhesion with pressureless sintering, it is required that interfacial sintering occurs among the paste and the substrate and die surfaces. This promotes stronger interfacial bonding than with resin alone and thus greater adhesion performance at higher temperatures, as needed for high power devices.

Table II. High Temp. Die Shear Strength (260°C)

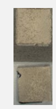
	FOR1	FOR2	FOR3	FOR4
Shear Force (7x7mm Die on Ag Leadframe) [kg]	36	72	98	74
HTDSS Failure Mode				

Table II shows differences in high temperature shear strength measurements for each formulation change. Changing the silver package from Ag1 in FOR1 to Ag2 in FOR2 significantly improves the hot die shear adhesion, which may be correlated with improved interfacial sintering, as seen with the SEM slices shown in Fig. 1. Silver loading is also an important factor that supported improved interfacial sintering in FOR2.

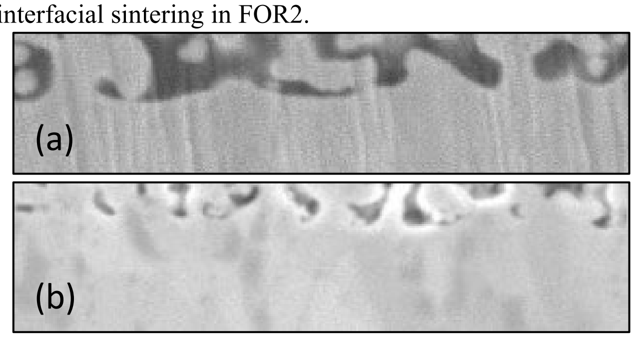


Figure 1. Interfacial sintering of (a) FOR1 and (b) FOR2 on Ag metallized substrates (shown as bulk on bottom half of images).

Due to interfacial sintering already being established with FOR2, further changing of the silver loading and the resin system had smaller but still significant effects on HTDSS. The increase in silver loading from FOR2 to FOR3 likely promotes additional sintering, increasing sintering structure strength, which then increases bulk shear strength of the material. Changing the resin chemistry from FOR3 to FOR4 may have the opposite effect by disrupting sintering, reducing the shear strength of the material. Compatibility of the resin for the silver package is a critical factor for sintering. Overall, the differences in HTDSS values between FOR2, FOR3, and FOR4 are likely due to differences in sintering structure and interfacing caused by the formulation changes.

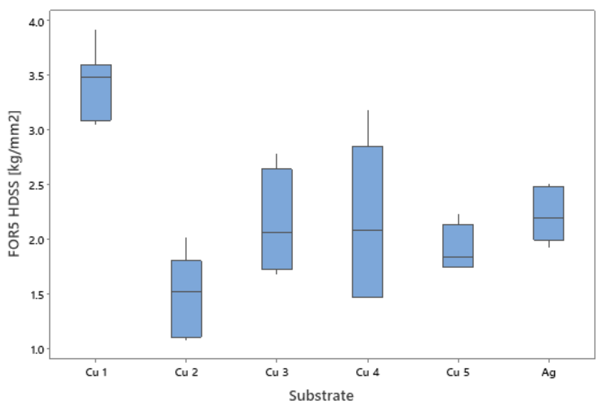


Figure 2. High temperature die shear strength of FOR5 on various copper and silver substrates.

Copper surfaces pose additional challenges to sintering due to the intermetallic nature of the interface sintering, as well as surface contaminants, such as oxides and anti-tarnish agents, on bare Cu surfaces. These challenges can be overcome by carefully designing the silver package and silver loading as seen for FOR5. High temperature die shear strength of FOR5 appears to be stable, >1.5 kg/mm^2, on a variety of Cu lead frames as shown in Fig. 2. However, many changes to the Cu surfaces such as special coatings, different surface roughness, Cu alloy, and surface grain size/orientation, can potentially impact interfacial bonding to Cu as shown by variations in the average shear force.

C. *Electrical and Thermal Conductivity*

Table III. Thermal Cond. and Electrical Resistivity

	FOR1	FOR2	FOR3	FOR4	FOR5
Bulk TC [W/m·K]	70	150	200	65	130
Volume Resistivity [ohm·cm]	7.5E-6	1.4E-5	1.0E-5	1.0E-5	7E-6

One purpose of using a pressureless sintering material is to achieve high thermal and electrical conductivities consistently across the bondline. The silver particles in the die attach paste sinter together, forming channels for thermal conduction from the die to substrate surfaces. We see in Table III that FOR1 can already achieve thermal conductivity of 70 W/m·K despite sub-optimal sintering and interfacing as shown by adhesion testing.

Improving the bulk sintering by optimizing silver package and silver loading shows significant increases to thermal conductivity as seen when FOR1 and FOR2 are compared. There is a further improvement in thermal conductivity observed when there an increase in silver loading from FOR2 to FOR3. Finally, as resin chemistry is adjusted from FOR3 to FOR4, bulk sintering is likely hindered, reducing the thermal conductivity of FOR4. Overall, thermal conductivity is sensitive to the bulk sintering of pressureless sintering die attach pastes and each formulation component can have both detrimental and beneficial effects on conductivity.

D. *Mechanical Properties*

Table IV. Modulus vs. Temperature

	FOR1	FOR2	FOR3	FOR4	FOR5
Modulus E' at 25°C [GPa]	15.4	20.0	27.5	15.7	21
Modulus E' at 250°C [GPa]	7.1	10.6	13.9	8.1	9

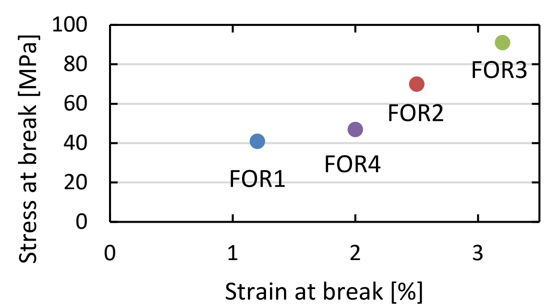


Figure 3. Stress at break vs strain at break of various formulations.

As with conductivity, mechanical properties are influenced heavily by the sintering capabilities of the formulation. The extent of sintering determined by previous material properties screening, appears to impact the mechanical performance of these materials. Modulus measurements and tensile properties are summarized in Table IV and Fig. 3 respectively. As sintering is improved from FOR1 to FOR2 and from FOR2 to FOR3, all material properties presented here (i.e., modulus, strain at break, fracture strength) increase, supposedly due to increased sintering and a bulkier sintering structure. When sintering is disrupted, as evidenced by conductivity and adhesion drops observed with FOR4, the mechanical properties are reduced accordingly.

An additional observation from the tensile properties in

Fig. 3 is that these materials are brittle with little plasticity. This poses challenges in designing material capable for surviving reliability testing for semiconductor applications. Although mechanical performance can be improved with increased sintering, dense structures, correlated to higher strength, also bring about higher modulus and accordingly higher stress within the bondline. These properties need to be balanced such that strength increases are greater than corresponding modulus increases. Understanding how sintering is impacted by formulation components allows for tuning and optimization of properties for both material and reliability performance.

E. Reliability

Reliability evaluations bring together many different competing material properties and package constraints in a balance of forces. The first screening method used for material reliability performance was acoustic imaging conducted at key stages during reliability testing. As shown in Fig. 4, results indicate that though all 4 materials were able to withstand MSL3 testing, FOR1 shows significant degradation by the time TC1000 has been reached. As shown previously, FOR1 shows lower thermal conductivity performance and the lowest adhesion by a large margin compared to the other formulations which indicates the reliability is tied to the materials ability to form and maintain a strong sintering network. Through manipulation of the silver package and silver loading, FOR2-4 all show improvement in long term reliability compared to FOR1.

Figure 4. Acoustic imaging results at various key reliability stages for each formulation.

Following acoustic imaging, representative parts were pulled from the experiment for cross-sectioning and SEM imaging. These images were analyzed for any defects in bulk sintering and sub/die interfacing. One such defect which is common of pressureless sintering material following reliability is cracking which originates at the die edge and moves toward the center over the course of thermal cycling. All FOR had cracks measured and summarized in Table V.

Table V. % Cracking in Bondline @ TC1000

	FOR1	FOR2	FOR3	FOR4
% of Bondline With Cracking	15	9	3	9

The increase in crack length observed with FOR1 is consistent with its acoustic imaging performance. The less dense sintering structure shows more significant reliability cracking. Contrasting this is FOR3 results. Through optimization of silver package and silver loading, higher levels of sintering density are achieved and as a result the die attach material is more resistant to the cracking failure mode. FOR2 is an intermediate formulation between FOR1 and FOR3 and, just as was observed in all material characterization previously discussed, cracking performance correlates with the sintering density.

IV. Conclusion

In this paper, we have demonstrated that material performance and mechanical properties can be optimized to enhance reliability performance. Reliability appears to improve as adhesion strength, thermal conductivity, and strain/stress at break are increased. These improvements are achieved by formulation adjustments, such as resin chemistry, silver loading, and silver packaging changes, that promote sintering on both the interfaces and within the bulk of the die attach bondline. Ultimately, these findings show that careful formulation design is critical to material and reliability performance in die attach applications.

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