Improving Semiconductor Reliability of Silver Sintering Die-Attach Adhesives for Large Die on Copper Lead Frames

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***Abstract*—Emerging trends like 6G Telecom and Electric Vehicles (EVs) are driving advancements in semiconductor packaging, specifically in back-end assembly. These enabling technologies are focused on achieving higher functionality, improved connectivity at higher frequencies, smaller form factors, efficient heat dissipation, and reduced power consumption. The instrumental role of Wide-Band Gap semiconductors to enable high-frequency RF transmissions, and efficient power switching necessitates advancements in thermal dissipation and the ability to withstand higher thermo-mechanical stresses in next-generation power devices. Concurrently, the semiconductor industry has been seeking a lead (Pb) solder replacement with improved automotive reliability for over two decades. The lead-free alternatives need to be compatible with larger die sizes on metal lead frames and must align with the high productivity demands of semiconductor back-end processing. However, finding a suitable, drop-in lead-free solution that can address these challenges has proven to be highly challenging [1]. This paper describes the ongoing product development and comprehensive testing of a new hybrid silver sintering die-attach development with stress-absorbing additives specifically designed for large die on lead frame based applications following close collaboration between Henkel and CITC. This development work has been the result of the dire need to meet the industry's evolving trends and requirements towards higher power and sustainable products.**

***Index Terms*—Silver sintering; Hybrid sintering; Power semiconductors; Automotive reliability; Conductive die-attach; Pb solder replacement; Pb free.**

I. Introduction

Given the complex challenges encountered during the package assembly processes and the imperative to fulfill application-specific requirements, it is vital to assess the compatibility of individual components, processes, and materials [2–4]. Therefore, this study places specific emphasis on evaluating the die-attach layer, encompassing the assembly process and its impact on the reliability of the end product.

The choice of an appropriate die-attach material plays a critical role in package assembly. A review of die-attach materials for high-temperature applications can be found in [5–7]. Previously, high-lead (Pb)-based solders were mostly preferred due to their high melting point and relatively low stiffness. However, concerns regarding lead toxicity have led to restrictions on their usage. This has resulted in market demand for lead-free die-attach materials that offer superior thermal properties and improved thermo-mechanical stability. Addressing the challenge of reducing thermo-mechanical stresses between a large die with a coefficient of thermal expansion (CTE) of ∼3ppm/^{o}C and copper lead frames (∼17ppm/^{o}C) require a multi-disciplinary approach, encompassing thermal, electrical, mechanical, and material science domains. Traditional lead-free solders are not viable alternatives for semiconductor die-attach due to their low melting point. The reliability of lead-free solders with high-melting temperatures for harsh environmental applications has been a subject of comprehensive studies on its own [8].

Sintering technology presents a promising solution that offers several advantages compared to traditional solders. The sintering process involves the fusion of metal (micro/nano) particle precursors in paste form under heat and optionally pressure. One of the main benefits of sintering is its ability to sinter at relatively low temperatures, typically between 200–300^{o}C, and achieving the high-melting-point characteristics of a bulk metal after sintering. Sintered joints exhibit improved thermal stability and enhanced thermal performance, making them highly suitable for high-temperature and high-power applications. However, the success of sintering heavily relies on the sintering paste chemistry and precise processing conditions. In electronic packaging, sintering materials are typically composed of silver or copper base metals. Copper is favored in terms of process compatibility, but sintering remains challenging due to the reactivity and sensitivity of copper precursors (risk of Cu oxidation/corrosion). As a result, silver sintering has emerged as the most promising and reliable lead-free die-attach solution [9–16].

Pressure-less silver sintering materials provide an excellent basis to improve performance, both thermal and electrical, as well as thermo-mechanical reliability compared to solders. Furthermore, from a practical point of view, pressure-less silver sintering is expected to enable increased production output as compared to solders and pressure-assisted sintering. However, a significant challenge with pure solvent-based silver sintering (pressure-less) materials is their inherent porosity, which leads to microscopic stress concentrations within the die-attach material and allows moisture ingress. This, in turn, reduces the Moisture Sensitivity Level (MSL) of the finished component and increases its brittleness compared to bulk silver material. To address these concerns, an effective approach has been the incorporation of an organic resin phase into the sintered joint, referred to as 'hybrid silver sintering.' This method minimizes porosity through filling and sealing, thereby improving the overall flexibility and toughness of the sintered bulk material. As a result, the thermo-mechanical performance of the sintered die-attach joint during stressful Moisture Sensitivity Level (MSL) and Thermo-Mechanical Cycling Lifetime (TMCL) reliability testing is enhanced. However, it should be noted that pressure-less hybrid silver sintering materials often exhibit lower thermal performance as compared to pure silver or pressure-assisted silver, which was previously investigated on similar silver sintering materials with metal-organic and resin-reinforced technology [17–19].

In this study, a new class of experimental 'stress absorbing' hybrid silver sintering die-attach materials ('EXP3' and 'EXP5') with ∼150–200 W/m-K effective bulk thermal conductivity were investigated. The fundamental difference between these two new die-attach materials is that EXP5 has a higher bulk sintering density and consequently higher modulus than EXP3. These materials were developed to pass severe Automotive Electronics Council (AEC) Q100 and Q101 (respectively for Integrated Circuits and Discretes) reliability test requirements (up to 2000 thermal cycles -55^{o}C/$+150^{o}$C for highest Grade 0). This is achieved by optimizing the silver paste formulation with special filler packages and stress-absorbing additives, to increase the bulk sintering network and interfacial sintering to die and lead frame, next to improving MSL and thermal cycling performance. The thermo-mechanical reliability of these stress-absorbing hybrid silver sintering materials was benchmarked against a commercially available hybrid silver sintering material ('8068TI') with ∼165 W/m-K bulk conductivity without the stress-absorbing feature [1] (for reference, LOCTITE® ABLESTIK ABP 8068TI is successfully released in automotive power semiconductors with die sizes up to ∼3×3mm, but facing thermal cycling limitations on a copper lead frame with larger die sizes).

This work focuses on examining the package assembly process and thermo-mechanical reliability testing. The following section II provides a detailed description of the various steps involved in the test package assembly. The subsequent section III discusses the hot die-shear strength experiments and the experimental findings from the Thermo-Mechanical Cycling Lifetime (TMCL) testing. This section includes the functional device's electrical measurement (changes in electrical resistance R_{DS}(on)) during thermal cycling for the new class of hybrid silver sintering die-attach materials with stress-absorbing technology versus commercially available reference material. This paper concludes with section IV including remarks on the potentially broader use of the hybrid silver sintering die-attach adhesives towards larger die sizes on copper-based lead frame applications.

II. Experimental Methods

A. Sample preparation

Silicon-based N-channel enhancement mode Field Effect Transistor (FET) with TrenchMOS technology was chosen as a test vehicle in this study. These devices are commercially used in high-performance automotive systems with a maximum power rating of up to 333W. The MOSFETs were assembled in Power Quad Flat No-Lead (PQFN) surface mount packages based on the following steps.

(a) The package assembly process commences with the preparation of the lead frame. As depicted in Fig. 1a, the package substrate (lead frame) is made of fully hardened C194 copper with 500μm thickness. To enhance adhesion, the lead frame surface was plated. Two distinct lead frame finishing options were examined: (i) Nickel-Palladium-Gold (NiPdAu, also known as 'PPF') and (ii) Silver. Prior to processing, the lead frames were treated with Argon plasma to remove surface contamination.

(b) Next, the commercial and experimental die-attach materials (8068TI, EXP3, EXP5) were dispensed in a snowflake pattern (Fig. 1b) using a Musashi Image Master 350PC Smart Dispense Robot equipped with a 25-gauge needle and applying 100–200KPa of pressure.

(c) Die placement was performed on a Finetech Sigma Fineplacer equipped with a position-controlled z-axis. The Silicon MOSFETs dies with 4.5×5.5×0.17 mm dimensions and silver backside metallization (Ag BSM) were carefully picked and placed with a placement force of approximately 0.3N (Fig. 1c). Once the die is properly positioned, the sintering process was carried out in a Budatec VS160 vacuum oven under Nitrogen. The first step involves staging at 130 ^{o}C for two hours, followed by pressure-less sintering at 200 ^{o}C for one hour. After sintering, all samples were inspected with a confocal microscope to measure the die-warpage.

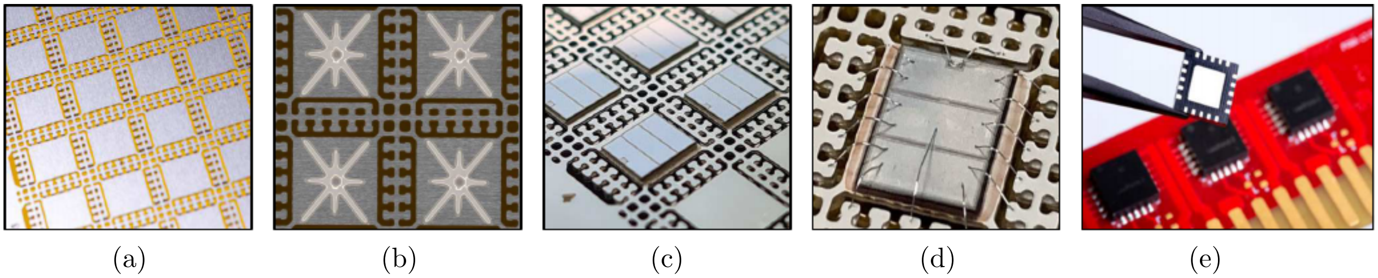

Fig. 1. A pictorial representation of the package assembly processes is shown. The various stages of the assembly process are explained in steps (a) to (e) in section II. *A*.

(d) Electrical connections were established to the lead frame through wire bonding (Fig. 1d). A 4-point probe configuration was used for all terminals; Source, Gate, and Drain.

(e) The final step involves transfer molding. This was performed with Sumitomo EME-G700LA epoxy molding compound at 175^{o}C. The molded devices were further laser marked, singulated, and soldered with SAC305 alloy onto a Printed Circuit Board (Fig. 1e). These soldered devices were further subjected to Moisture Sensitivity Level (MSL3) and TMCL tests as described in the following subsection.

In this study, six types of functional test packages (3 die-attach materials and 2 lead frame metallizations) were prepared with over 32 packages per leg. The Bond-Line Thickness (BLT) of the sintered die-attach layer was evaluated using confocal optical microscopy. The typical wet BLT after die placement was ∼45–50um and the average dry (sintered) bond line thickness was ∼28–37um. In addition to the functional test packages, a series of test samples were prepared in a similar process to evaluate the Hot Die-Shear Strength (HDSS) at typical solder reflow temperature (260^{o}C) for both commercial and experimental die-attach materials. A dummy silicon die of 4.9×4.6×0.52mm with silver backside metallization was sintered on a 2mm copper flange with both NiPdAu and Silver metallization using the same staging and sintering profile. The die-shear experimental results were evaluated in comparison with the die-warpage measurements after sintering.

B. Thermo-Mechanical Cycling Lifetime Experiments

To assess the reliability of the PQFN test packages prepared with commercial and experimental hybrid silver sintering die-attach adhesives, Thermo-Mechanical Cycling Lifetime (TMCL) experiments were conducted. Before commencing the TMCL testing, all packages underwent the Moisture Sensitivity Level 3 (MSL3) pre-conditioning step. The MSL classification system aids to assess the moisture sensitivity of an electronic component during storage before assembly, particularly surface mount devices (SMDs). This MSL3 step involved drying the PQFN packages at 125^{o}C for 24 hours, followed by exposure to 60% relative humidity at 60^{o}C for 42 hours. Subsequently, the PQFN packages were subjected to three consecutive reflow soldering cycles (260^{o}C) within one week.

The TMCL experiments were conducted based on the guidelines provided by AEC Q100 and Q101 as mentioned earlier. These stress tests are recommended for qualifying automotive-grade Integrated Circuits (ICs) and discrete semiconductors involving temperature cycling from -55^oC (compression state) to 150^{o}C (expansion state), as depicted in Fig. 2. The temperature cycling rate was maintained at approximately 1–2 cycles per hour. Throughout the testing process, the device's electrical performance was monitored intermittently.

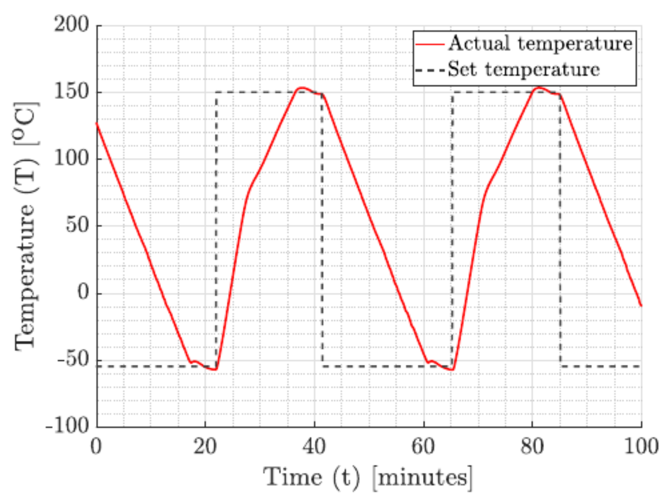

Fig. 2. The temperature cycling profile -55^oC to 150^{o}C shown is based on the automotive AEC norms for ICs & discrete semiconductors and the JEDEC temperature cycling standards.

The on-state electrical resistance (R_{DS}(on)) of the N-channel MOSFET was measured at specific thermal cycle intervals: 0, 100, 500, 1000, 1500, and 2000 cycles. The PQFN device was operated under a forward source-drain bias with a positive gate-source voltage (V_{GS}) of 20V and a drain-current (I_D) of 2A for a duration of 5ms. The reliability of the die-attach joint was monitored effectively during thermal cycling based on intermittent electrical measurements. This was possible since the device's drain terminal is electrically connected to the package substrate through the die-attach interface. The subsequent experiment results section discusses in detail the hot die-shear strength test results in comparison to the die-warpage measured after sintering, and the in-package electrical measurements on the PQFN test vehicle during TMCL testing.

III. Experimental Results

A. Hot Die-Shear Strength Experiments

The die-shear strength of both commercial and experimental die-attach materials was evaluated at the typical lead-free reflow soldering temperature of 260^{o}C to investigate and benchmark the adhesive and the sintering performance. The experiments were conducted using a Universal Bond Tester (Royce 650). The evaluation encompassed all three die-attach materials 8068TI, EXP3, and EXP5 on both copper lead frame metallizations (NiPdAu and Ag). The results of the HDSS experiments are presented in Table I. Both experimental hybrid silver sinter materials exhibited good adhesion/sintering on NiPdAu and Ag finish lead frames, yielding HDSS in the range of approximately 14 MPa ($\sim$1.4 kgf/mm^2 which is in line with typical application requirements). Cohesive failure modes within the sintered die-attach bond line were observed in all cases. However, for commercial 8068TI on NiPdAu metallization, a significantly lower HDSS of approximately 5 MPa was observed, with adhesive failure occurring at the NiPdAu interface. On the other hand, when 8068TI was used with the silver finish, failure occurred at the interface of the silver backside of the die with an HDSS of approximately 14 MPa (like EXP3 and EXP5).

TABLE I
Hot Die-Shear Strength (HDSS) of three hybrid silver sintering die-attach adhesives at 260^{o}C on two different lead frame metallizations.

HDSS [MPa]	8068TI			EXP3			EXP5		
NiPdAu	3.2	7.1	5.4	13.8	14.7	15.6	12.8	15.2	11.8
	3.5	2.9	4.8	12.2	13.2	14.6	13.7	16.1	16.2
	Avg. 4.48 MPa			*Avg. 14.02 MPa*			*Avg. 14.3 MPa*		
Silver	15.0	17.2	17.4	11.1	15.7	13.5	15.2	11.5	13.7
	10.9	10.1	12.5	11.2	11.5	13.6	13.5	12.4	14.6
	Avg. 13.85 MPa			*Avg. 12.76 MPa*			*Avg. 13.48 MPa*		

The difference in thermal expansion CTE of the copper lead frame ($\sim$17 ppm/^{o}C) and the silicon die ($\sim$3 ppm/^{o}C), causes measurable warpage at room temperature after sintering at $\sim$200^{o}C. This is a direct result of the residual stress within the sintered die-attach bond line after cooling down. It is driven by the stiffness, CTE, and the temperature at which sintering occurs, and the die-attach bond line solidifies (which was found experimentally to be around 150^{o}C). Lower-than-expected warpage values are reminiscent of relaxation within the die-attach bond line layer. The die-warpage was experimentally measured using a Keyence laser confocal surface profiler. The results are tabulated in Table. II. In this configuration, Finite Element Method (FEM) simulations confirmed that the material properties (modulus, CTE, and thickness) of the die-attach layer have a neglectable influence on the die-warpage itself. Rather it is fully defined by the mechanical properties of the lead frame and die.

TABLE II
Die-warpage for all three die-attach materials onto two lead frame finishes measured after the sintering process over two axes of the die (short and long).

Warpage [μm]	Die short side - 4.5mm			Die long side - 5.5mm		
	8068TI	**EXP3**	**EXP5**	**8068TI**	**EXP3**	**EXP5**
NiPdAu	*0.5*	5.8	6.6	*0*	9	9.3
Silver	*2.3*	5.2	5.5	*4.3*	8.6	10.2

The experimental 'stress-absorbing' hybrid silver sintering materials (EXP3 and EXP5) demonstrate a curvature of approximately 10µm along the long side of the die and around 6µm along the short side on both NiPdAu and Silver metalized lead frames. These results confirm a favorable bonding/sintering between the die and lead frame, contributing to the observed warpage of the complete stack. The die-warpage with EXP3 and EXP5 aligns within 30% of that obtained from FEM simulations. In contrast, the commercial silver sintering material (8068TI) on NiPdAu exhibits no warpage indicating poor adhesion and delamination at the die edges. Lower-than-expected warpage was observed for 8068TI material on Silver metalized lead frames. The poor adhesion of 8068TI to NiPdAu is in good alignment with the results from the Hot Die-Shear Strength (HDSS). Contradicting evidence was observed for 8068TI on Silver metalized lead frames. The HDSS on Silver indicates good adhesion, however, the die-warpage measured suggests some relaxation within the 8068TI material.

In summary,

- The new 'stress-absorbing' hybrid silver sintering materials (EXP3 and EXP5) demonstrate high die-shear strength at 260°C on both NiPdAu and Silver metalized lead frames. These findings are further supported by die-warpage measurements conducted on functional devices after sintering.
- The 8068TI reference material shows lower adhesion to these specific NiPdAu finished PQFN lead frames. This was confirmed through hot die-shear strength and die-warpage measurements. 8068TI adhesion to these specific Silver metalized lead frames indicates higher HDSS values, however die-warpage measurements indicate some form of mechanical relaxation.

B. Electrical Measurements

The electrical on-state resistance (R_{DS}(on)) refers to the resistance measured across the drain-source terminals of the packaged device under forward bias. It is a combination of the electrical resistances of the die (R_{Die}), die-attach (R_{DA}), lead frame (R_{LF}), and the package substrate solder joint interface (R_S). It's assumed that the solder joint interface remains relatively stable during the TMCL test. This assumption is based on the matched coefficient of thermal expansion (CTE) between the copper lead frame and the copper metallic pad on the PCB substrate. Hence, changes in the electrical resistance R_{DS}(on) are expected to correspond to degradation, specifically in the die-attach bond line which is more prone to failure as compared to other materials during cyclic loading. The packaged devices were subjected to thermal cycling from -55^oC to 150^oC, and the electrical resistance (R_{DS}(on)) was measured intermittently at room temperature ($\sim 25^oC$). The test results are presented in Fig. 3.

The measurement results were analyzed based on Weibull probability distribution. Weibull probability analysis refers to a statistical method of analyzing and interpreting the failure data based on the Weibull distribution. It involves fitting the observed failure data to the Weibull distribution, thereby estimating the shape and scale parameters of the distribution. The shape parameter β represents the slope of the fitted line and the scale parameter η is related to the intercept (electrical shift or drift). Accordingly, the electrical resistance (R_{DS}(on)) of the packages measured at fixed intervals (0, 100, 500, 1000, 1500, and 2000 thermal cycles) were plotted against the percentage distribution (Fig. 3). For each sample variation, the data from every cycle was fitted with a straight line to determine the shape and scale parameters. The evolution of the shape β and scale η parameters over thermal cycling up to 2000 cycles can be visually observed in Fig. 3. From a physical context, the scale parameter (η) signifies the shift or drift in electrical performance (typically degradation by higher resistance values), where the shape parameter (β) reflects the distribution of the degraded samples after thermal cycling.

For the PQFN packages with NiPdAu finish, a noticeable drift in R_{DS}(on) is observed with increasing thermal cycles. In particular, 8068TI and EXP5 show more shifts to the right

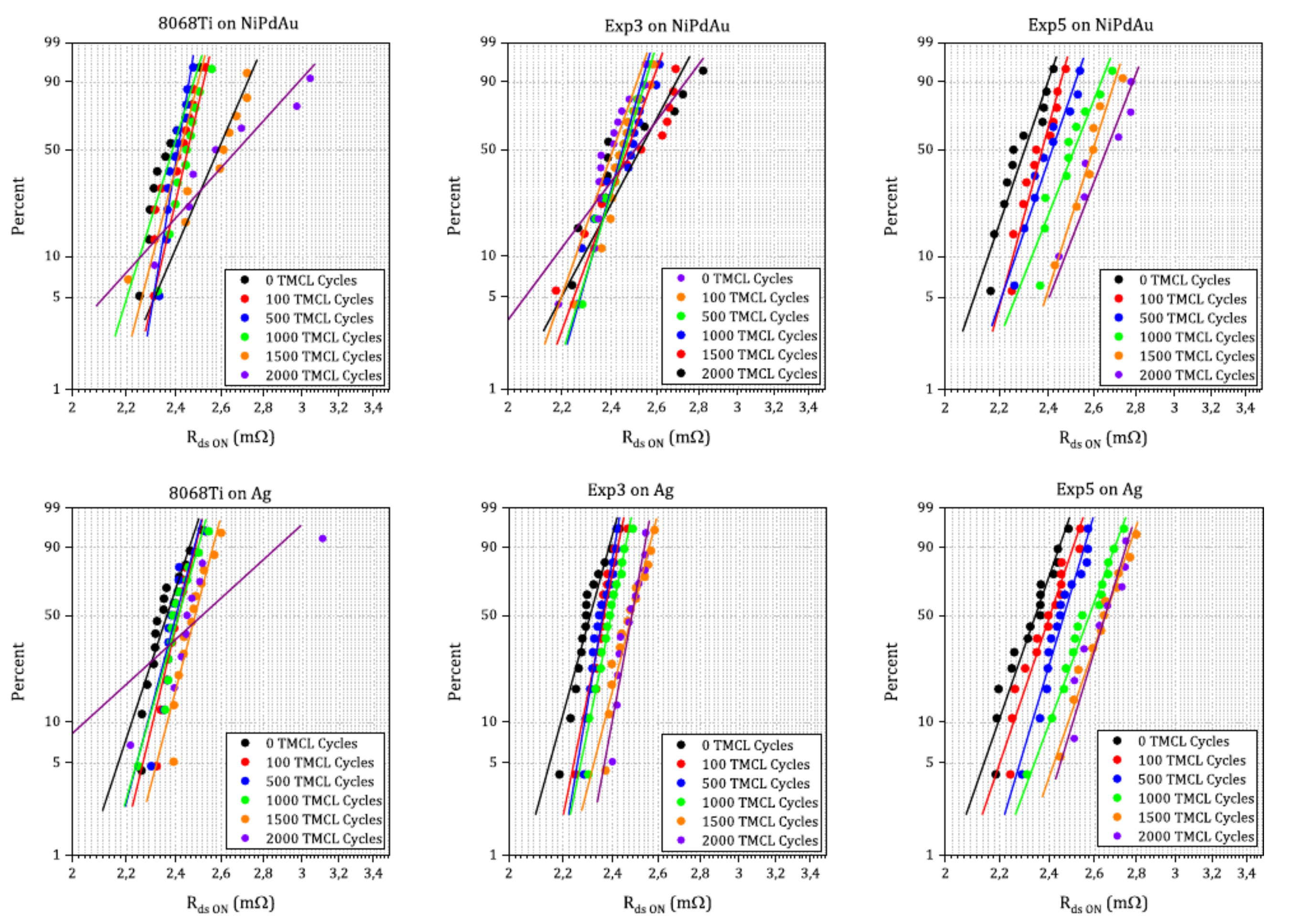

Fig. 3. Weibull probability plots showing the electrical on-state resistance (R_{DS}(on)) measured on all three tested die-attach materials (8068TI, EXP3, and EXP5) on two PQFN lead frame metallizations (NiPdAu and Ag) up to 2000 thermal cycles (-55^oC to 150^oC).

indicating a higher degree of degradation compared to EXP3, leading to considerably higher electrical resistance as depicted in Fig. 3. Conversely, the slope of the line decreases with increasing thermal cycling in the case of 8068TI and EXP3. This suggests that the degree of performance diverges among the samples, implying the presence of a possible stochastic degradation mechanism. In the case of the die-attach materials (8068TI, EXP3, and EXP5) on Silver (Ag) finish, a relatively limited drift in R_{DS}(on) is observed as compared to NiPdAu finish, suggesting a more gradual and slower degradation process during thermal cycling. Besides, the measurement data does not exhibit significant variations in comparison to the NiPdAu test samples. This indicates that the degree of degradation is relatively consistent among all samples with a Silver (Ag) finish, with EXP3 showing the most stable electrical performance with the lowest electrical drift after 2000 thermal cycles.

Another statistical aspect of interpreting the experimental measurements is to understand the dispersion present within the datasets. The interquartile range (IQR) is a robust statistical method to evaluate the dispersion. The IQR method provides a summary of data spread by focusing on the middle 50% of observations between the 25th and 75th percentiles. Based on the experimental measurement results shown in Fig. 3, the IQR was determined and visually represented in Fig. 4. These box plots effectively illustrate the central 50% data spread, while the whiskers indicate the 1.5IQR range. Additionally, Fig. 4 presents the mean, median, and outliers present in the measurement data, providing a comprehensive analysis of the thermal cycling datasets' characteristics.

The IQR data as presented in Fig. 4 clearly indicates that all three die-attach materials (8068TI, EXP3, and EXP5), when used with both NiPdAu and Ag finish lead frames on this specific PQFN test package, exhibit a shift of less than 20% in the electrical on-state resistance over 2000 thermal cycles. Notably, the EXP3 die-attach with stress-absorbing additive stands out, demonstrating a deviation of less than 10% on both lead frame metallizations. Meeting the stringent long-term reliability requirement of less than 10% variation in electrical resistance (R_{DS}(on)) is of utmost importance, especially for automotive grade semiconductor packages. In this regard, EXP3 convincingly meets this criterion with both NiPdAu and Ag finish PQFN copper lead frames on relatively large die size (∼4.5×5.5 mm).

In summary,

- A noticeable difference in the electrical performance during thermal cycling is observed between the 8068TI, EXP3, and EXP5 test samples on both lead frame metalization types; NiPdAu and Ag finish lead frames (Fig. 3 & 4).

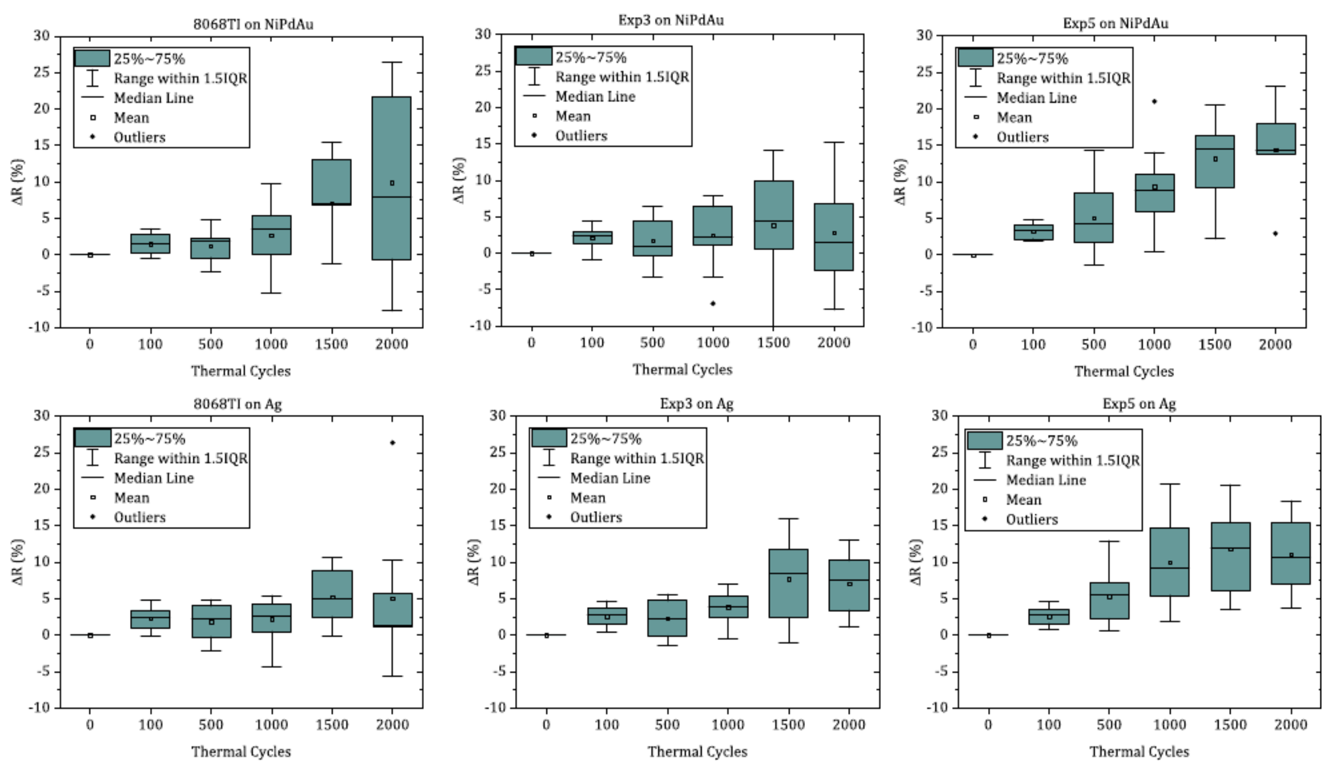

Fig. 4. Interquartile range (IQR) plots showing the percentage change in the electrical on-state resistance (R_{DS}(on)) measured on all three tested die-attach materials (8068TI, EXP3, and EXP5) on two PQFN lead frame metallizations (NiPdAu and Ag) up to 2000 thermal cycles (-55^{o}C to 150^{o}C).

- The new experimental hybrid silver sintering material EXP3 with stress-absorbing additives, exhibits the best resilience to thermo-mechanical loading. EXP3 demonstrates less than 10% deviation in R_{DS}(on) over 2000 thermal cycles on both copper lead frame types (with Ag finish giving the best test results versus NiPdAu).
- Comparatively, 8068TI reference material without 'stress-absorber' performs similarly well when used with Ag finish lead frames, but shows large variety in R_{DS}(on) test results on NiPdAu.
- The other new EXP5 material with 'stress-absorber' displays an R_{DS}(on) drift of $\sim$10% when used with Ag lead frames and $\sim$15% when used on NiPdAu finish lead frames.

IV. Discussions and Conclusions

This comprehensive test work on PQFN test packages with 4.5×5.5×0.17 mm die size demonstrates that all three hybrid silver sintering die-attach materials exhibit reasonably good to very good thermo-mechanical reliability performance based on electrical measurements. It became evident that the adhesion, sintering, and reliability performance of these three die-attach formulations on Ag finish is overall better as compared to NiPdAu finish lead frames. Notably, the experimental hybrid silver sintering die-attach materials (EXP3 and EXP5) with 'stress absorbing technology' demonstrate improvements compared to the commercially available (8068TI) reference material without 'stress-absorber' in terms of adhesion and sintering performance. The EXP3 die-attach formulation stands out in this specific PQFN test work with superior performance on both NiPdAu and Ag finish lead frames, as confirmed by hot Die-Shear experiments and automotive thermal cycling (TMCL) testing up to 2000 cycles ($-55/+150^{o}$C) with a maximum of 10% drift in R_{DS}(on). Similarly, the EXP5 die-attach formulation with higher bulk sintering density and consequently higher modulus than EXP3, shows improved adhesion in Die-Shear experiments compared to 8068TI reference material. However, the thermal cycling reliability performance of EXP5 falls somewhere between that of 8068TI and EXP3.

It is essential to mention, realize, and acknowledge that the outcome of all test work described in this study is based on the specific PQFN test package used and that the test results can be different on other test devices, such as different geometries (die size and thickness), die types (Si/SiC/GaN), backside metals (Ag/Au), lead frame finishes, surface roughness, etc. This understanding is crucial when selecting the most suitable die-attach material for specific applications, as the choice can significantly impact the overall performance and reliability of the package. For instance, for applications with a thicker lead frame and thinner die, and vice versa, EXP5 with higher bulk sintering density and higher modulus may perform better than EXP3 having lower modulus.

To summarize, the new experimental hybrid silver sintering materials with stress-absorbing feature exhibit commendable die-shear strength at elevated temperatures (260^{o}C), which are further supported by die-warpage measurements. Furthermore, the comprehensive thermo-mechanical cycling test results strongly indicate that the stress-absorbing hybrid silver sintering technology offers suitable die-attach solutions with enhanced thermo-mechanical reliability for larger die sizes on copper lead frame applications. With the introduction of stress-absorbing additives, the application space of this 'next generation' of hybrid silver sintering die-attach adhesives, developed for copper-based lead frames, can be expanded from typical die sizes of $\sim$3×3mm in the past, towards $\sim$5×5mm and above, by qualifying the severe automotive AEC Q100 and Q101 reliability test requirements (2000 thermal cycles $-55/+150^{o}$C for highest Grade 0). Besides, this pressure-less hybrid silver sintering technology offers other benefits such as high thermal conductivity, sustainable lead-free composition, and well-established dispensing application using existing die-attach equipment and processes proven in high-volume IC and Discrete production.

Acknowledgment

The authors extend their sincere gratitude and recognition to all other Henkel Product Development and Application Engineering colleagues, as well as Dave Reijs and other CITC colleagues involved for their precise and comprehensive test work, next to their valuable support and input throughout this extensive investigation. We also would like to acknowledge the appreciated assistance of SENCIO BV in Nijmegen (NL), providing their transfer molding knowledge and capabilities to encapsulate the PQFN test parts prior to testing.

References

[1] R. d. Wit, "Silver sintering die attach developments for rf, power and automotive applications," in *2021 23rd European Microelectronics and Packaging Conference & Exhibition (EMPC)*, 2021, pp. 1–4. DOI: 10.23919/EMPC53418.2021.9584971.

[2] Z. Chen, J. Zhang, S. Wang, and C.-P. Wong, "Challenges and prospects for advanced packaging," *Fundamental Research*, 2023, ISSN: 2667-3258. DOI: https://doi.org/10.1016/j.fmre.2023.04.014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2667325823001334.

[3] D. R. Frear, L. N. Ramanathan, J.-W. Jang, and N. L. Owens, "Emerging reliability challenges in electronic packaging," in *2008 IEEE International Reliability Physics Symposium*, 2008, pp. 450–454. DOI: 10.1109/RELPHY.2008.4558927.

[4] H. Wang *et al.*, "Transitioning to physics-of-failure as a reliability driver in power electronics," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 1, pp. 97–114, 2014. DOI: 10.1109/JESTPE.2013.2290282.

[5] K. Siow, *Die-attach materials for high temperature applications in microelectronics packaging*, Oct. 2018.

[6] V. R. Manikam and K. Y. Cheong, "Die attach materials for high temperature applications: A review," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 1, no. 4, pp. 457–478, 2011. DOI: 10.1109/TCPMT.2010.2100432.

[7] H. S. Chin, K. Y. Cheong, and A. B. Ismail, "A review on die attach materials for sic-based high-temperature power devices," *Metallurgical and Materials Transactions B*, vol. 41, pp. 824–832, 2010.

[8] J. Wang, S. Xue, P. Zhang, P. Zhai, and Y. Tao, "The reliability of lead-free solder joint subjected to special environment: A review," *Journal of Materials Science: Materials in Electronics*, vol. 30, May 2019. DOI: 10.1007/s10854-019-01333-w.

[9] S. A. Paknejad and S. H. Mannan, "Review of silver nanoparticle based die attach materials for high power/temperature applications," *Microelectronics Reliability*, vol. 70, pp. 1–11, 2017, ISSN: 0026-2714. DOI: https://doi.org/10.1016/j.microrel.2017.01.010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0026271417300161.

[10] S. Fu, Y. Mei, G.-Q. Lu, X. Li, G. Chen, and X. Chen, "Pressureless sintering of nanosilver paste at low temperature to join large area (≥100mm2) power chips for electronic packaging," *Materials Letters*, vol. 128, pp. 42–45, 2014, ISSN: 0167-577X. DOI: https://doi.org/10.1016/j.matlet.2014.04.127. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0167577X14007046.

[11] W. Liu *et al.*, "Recent progress in rapid sintering of nanosilver for electronics applications," *Micromachines*, vol. 9, p. 346, Jul. 2018. DOI: 10.3390/mi9070346.

[12] H. Yan, P. Liang, Y. Mei, and Z. Feng, "Brief review of silver sinter-bonding processing for packaging high-temperature power devices," *Chinese Journal of Electrical Engineering*, vol. 6, no. 3, pp. 25–34, 2020. DOI: 10.23919/CJEE.2020.000016.

[13] Y. Liu, H. Zhang, L. Wang, X. Fan, G. Zhang, and F. Sun, "Effect of sintering pressure on the porosity and the shear strength of the pressure-assisted silver sintering bonding," *IEEE Transactions on Device and Materials Reliability*, vol. 18, no. 2, pp. 240–246, 2018. DOI: 10.1109/TDMR.2018.2819431.

[14] W. Schmitt, L. M. Chew, and R. Miller, "Pressure-less sintering on large dies using infrared radiation and optimized silver sinter paste," in *2018 IEEE 68th Electronic Components and Technology Conference (ECTC)*, 2018, pp. 539–544. DOI: 10.1109/ECTC.2018.00085.

[15] K. Sugiura *et al.*, "Reliability evaluation of sic power module with sintered ag die attach and stress-relaxation structure," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 9, no. 4, pp. 609–615, 2019. DOI: 10.1109/TCPMT.2019.2901543.

[16] L. A. Navarro *et al.*, "Thermomechanical assessment of die-attach materials for wide bandgap semiconductor devices and harsh environment applications," *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2261–2271, 2014. DOI: 10.1109/TPEL.2013.2279607.

[17] N. Mizumura and K. Sasaki, "Development of low-temperature sintered nano-silver pastes using mo technology and resin reinforcing technology," in *2014 International Conference on Electronics Packaging (ICEP)*, 2014, pp. 526–531. DOI: 10.1109/ICEP.2014.6826735.

[18] K. Sasaki, N. Mizumura, A. Tsuno, S. Yagci, and G. Kopp, "Development of low-temperature sintering nano-silver die attach materials for bare cu application," in *2017 21st European Microelectronics and Packaging Conference (EMPC) & Exhibition*, 2017, pp. 1–5. DOI: 10.23919/EMPC.2017.8346875.

[19] X. Hu *et al.*, "Microstructure analysis based on 3d reconstruction model and transient thermal impedance measurement of resin-reinforced sintered ag layer for high power rf device," in *2023 24th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*, 2023, pp. 1–7. DOI: 10.1109/EuroSimE56861.2023.10100799.