Pressure-less AgNP Sintering for High-power MCM Assembly for Extreme Environment Applications

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Abstract

Silver nano-particle (AgNP) sintering has been a promising bonding material for high-temperature applications. There is an increasing demand for designs implemented as multi-chip module (MCM) in the high-temperature markets, like the oil and gas industry, primarily because of MCM's smaller size, higher-performance capability, and higher overall reliability when compared to traditional high T_g printed circuit boards.

In this work, pressure-less AgNP sintering paste was used in the assembly of multi-chip modules. The assemblies included die-mounted on aluminum nitride and alumina substrates that were metallized with various thin and thick films. Sintered silver nano-particle attachments were also attempted for surface-mounted technology (SMT) chip components. Different assembly parameters such as bonding line thickness and sintering profiles were evaluated to discover the optimal assembly process window that would yield acceptable reliability for 250°C and higher ambient temperature applications. The assemblies were subjected to various tests including thermal cycling, high-ramp rate thermal shocks, and high-temperature storage tests. Shear strength measurements and analysis of the cross sections and fracture surfaces were performed to understand failure mechanisms.

One of the findings was a certain and unique failure mode associated with bonding of thin-film gold metallized surfaces using pressure-less silver nano-particles sintering. That failure mode begins after a short exposure to temperatures of 200°C and higher. However, silver nano-particle sintering on substrates metallized with thin-film silver and some thick-film formulations yields dramatically better results.

Key words

Die Attach Durability Test, MCM assembly, Pressure-less nano-Ag sintering, Thin-Film

I. Introduction

There is an increasingly high demand for extreme-temperature compatible electronic assemblies for use in oil and gas industry downhole applications. The ability to operate multi-chip modules in ambient temperatures above 250°C reduces the need for complex cooling methods and significantly improves overall system capability and reliability. High-melting point solders have been used for electronic assemblies with similar requirements. However, 250°C is excessive for the reliable operating envelope of such solders. In addition, due to environmental and health concerns, international legislation has placed increasing pressure to avoid high-lead solders. High-temperature, lead-free solders like BiAgX and $Au_{80}Sn_{20}$ have liquidus temperatures of 262°C [1], [2] and 280°C, respectively. Consequently, these solders are not well suited for continuous operation and mechanical stresses in 250°C ambient conditions. Non-eutectic liquid phase transient (LPT) bonding using AuSn pre-forms with excessive gold (over 80%) could achieve a much higher melting point joint [3], but its high modulus of elasticity leads to failures during thermal cycles. Pressure-assisted silver sintering and LPT bonding processes are excellent candidates for single die packaging, but are difficult to apply to multi-chip modules batch assembly methods, leading to low yields [4]. Sintered silver joining has received much attention as a potentially reliable bond for high-power, high-temperature module assemblies used in extreme environments. A sintered silver joint has excellent thermal and electrical conductivity that is superior to most commonly used high-temperature attachment materials. The porous micro structure and low homologous temperature are credited for sintered silver joint's high performance during thermal cycling and long-term, high-temperature aging [5].

Electro-migration is one of the main concerns with silver interconnects. However, internal data and external research indicate that clean, hermetically sealed packaging that is backfilled with inert gas reduces this phenomenon to manageable levels [6]. Application of suitable coatings reduces the possibility of electro-migration even further. Testing to confirm the effectiveness of these electro-migration mitigation techniques is ongoing, and is a subject of a separate paper.

Pressure-less micro-size particle Ag sintered joints on gold metallized substrates showed rapid degradation to failure at 300°C [7]. This work investigated if the failure mode would repeat with the nano-sized Ag particles. Evaluation included the attachment of die and passives with various thin-film and thick-film metallization types using pressure-less AgNP sintering.

All testing was done to meet MIL-STD-883 and other specific environmental requirements for hermetic MCMs used in downhole applications [8]. Acceptable shear strength was defined as 6.25MPa. Furthermore, one of the main goals of this study was to gauge manufacturability of the pressure-less AgNP sintering process.

II. Experiment setup

Silver or gold thin and thick films are the most commonly used metallization types on MCM substrates. Testing included gold thin-film substrates that underwent an annealing process. The rationale behind this was to decrease thin-film gold surface energy and increase grain size in attempt to mitigate the potentially high diffusion rates of silver from the sintered joint. Iridium as a high-density metal with good electrical and thermal properties was also investigated for compatibility with pressure-less AgNP process

Tests with thin-film metallization were performed on polished aluminum nitride substrates. An example of the assembled test vehicle on thin-film Ag is shown in Figure. 1. AlN substrates using physical vapor deposition (PVD) techniques with either:

a. Thin-film gold, 4µm
b. Thin-film gold, 4µm, annealed at 400°C for 1 hour
c. Thin-film iridium, 12nm
d. Thin-film silver, 800nm

Tests with thick-film metallization were performed on 99.6% as-fired alumina substrates. Alumina substrates were metallized with either:

e. Thick-film gold (Heraeus)
f. Thick-film silver-palladium (Heraeus)

Parts attached to thin film substrates consisted of an assortment of functional silver-metallized Si/SiC die, ranging from $1mm^2$ to $42mm^2$ and SMT chip packages ranging from 0402 to 1812. Terminal metallization of SMT parts were silver-palladium glass frit and immersion gold (<0.1µm thick). Average area of sheared attachment on thin-film samples was $10mm^2$. Average area of sheared attachment on thick-film substrates was $20mm^2$ in size. With shear tester maximum shear force capability of 500N, this translated into equipment limitation for thin-film and thick-film samples were 50MPa and 25Mpa respectively.

Figure 1. One of the test vehicles assembled on a Ag thin-film substrate

Multiple variables were introduced to evaluate the flexibility and readiness of the assembly process for batch production methods in manufacturing environments. AgNP paste (30- to 50-nm particle size) was deposited thru 50- and 75-micrometer thick stainless steel stencils using a stainless steel squeegee. Stencil snap-off, squeegee speed and pressure were varied to achieve wet paste heights ranging from 55 to 85 micrometers. Die and chip components were mounted onto the substrates with light (<25cN) tap force. Sintering was performed using a convection oven and die placement machine's thermal chuck. Sintering profiles were varied to establish process window, as shown in Figure 2.

A 50-µm stencil and sintering Profile 4 were chosen for test vehicle assembly.

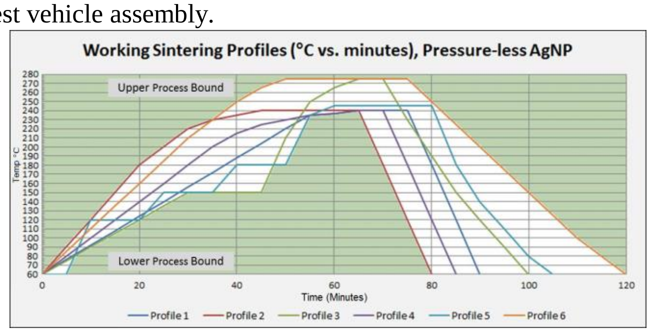


Figure 2. Varied sintering profiles

Test vehicles were visually inspected and components were shear tested using an F&K DEL 5600 shear tester. A baseline for the relative density of sintered silver joints was established. Results of short-term, high-temperature aging tests at 250°C and 280°C were used to screen out unacceptable materials and process parameters. XRF of fracture surfaces and 3D laser scanning microscope imaging of cross-sections were performed for detailed analysis. Upon completion of the screening, a range of suitable materials and the satisfactory process window were established.

Additional test vehicles were assembled for durability testing using only the promising candidate materials that were identified during the screening.

The durability testing consisted of three tests:

1. 100 thermal shocks from +35°C to +350°C with a 100°C per minute ramp rate and 5-minute dwells on thin-film Ag substrates.

2. 100 thermal shocks from -35°C to +280°C with 6-minute cycle times on thin-film Ag substrates. A profile of the shock cycle is shown in Figure 3.

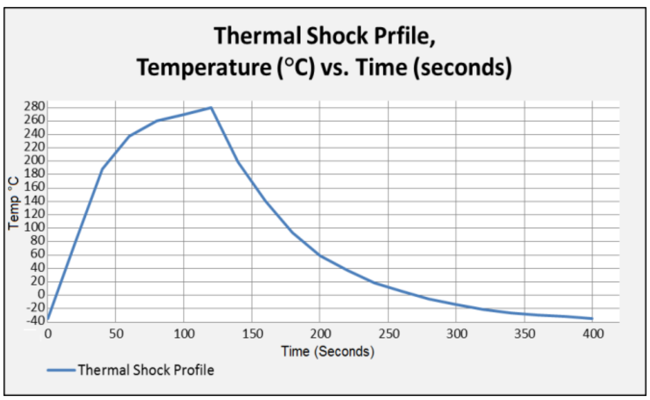


Figure 3. Thermal shock profile

3. Combined high-temperature aging and thermal cycling test on thin-film Ag, thick-film Au and AgPd substrates. The profile of the test involved eight iterations of 200-hour dwells at 280°C, followed by 25 cycles from -35°C to +280°C with a 7°C per minute ramp rate.

During the durability testing, the test vehicles were periodically visually inspected and components were shear tested. A change in microstructure and relative density of sintered silver joints was monitored. For detailed analysis, 3D laser scanning microscope imaging of cross-sections was performed.

III. Results

A. Screening tests on thin-film substrates

After assembly, the test vehicles were inspected with X-ray equipment to identify voids. As shown in Figure. 4, voiding of 1% or less was routinely obtained for die attach on the thin-film Au substrate. The die attach on other thin films had a similar voiding percentage.

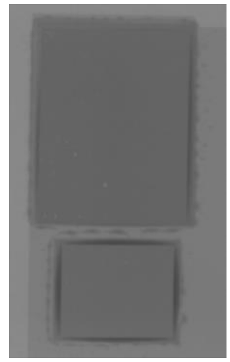


Figure 4. Representative X-Ray image of die attach on thin-film substrates

Figure 5 summarizes the results of the screen testing of thin-film test vehicle types a, b, c, and d. Shear strength data points at 50MPa represent the equipment limitation strength. The least-reliable results were obtained with as-built Au thin-film. Factors that marginally improved die attachment strength for thin-film gold were annealing and aging in an inert atmosphere. Aged shear strength results of AgNP sintered on thin-film iridium exceeded all variations of thin-film gold, but were still much lower than the results for thin-film silver. The dominant failure mode was the detachment of AgNP joins at the substrate interface. Out of all the screening test results on thin-films, only silver metallization had the sufficiently high thermo-mechanical performance. Consequently, it was chosen for the durability tests.

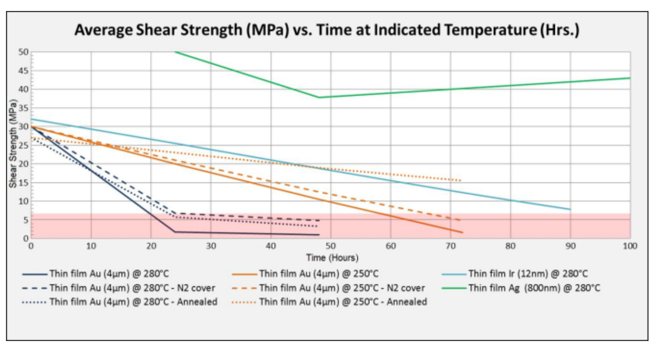


Figure 5. Summary of shear strengths on thin-film substrates

B. Screening tests on thick-film substrates

Figure 6 summarizes the results of the screen testing of thick-film test vehicle types e and f. Shear strength data points at 25MPa represent the equipment limitation strength for the attachment. AgNP joints on gold and silver-palladium thick-film metallization showed good shear strength with aging and were chosen for durability tests. The dominant failure mode at later stages of aging was cohesive failure inside sintered AgNP joints.

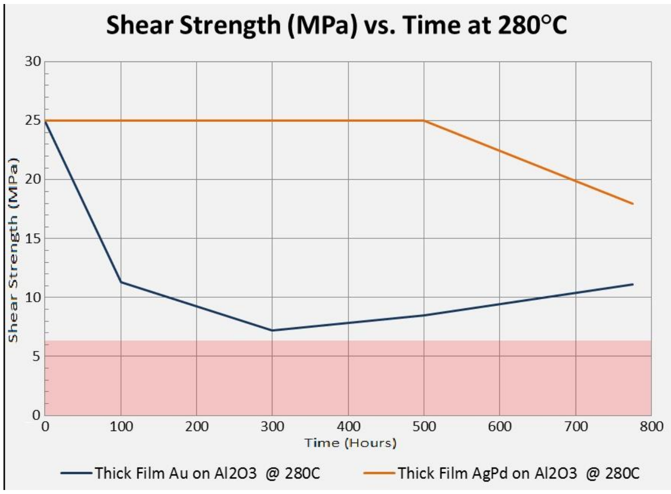


Figure 6. Summary of shear strengths on thick-film substrates

C. Screening tests of SMT chip parts attachment

SMT chip components with gold terminations had similar failures as die attachments on thin-film gold, resulting in low shear strength. Pressure-less AgNP attach of AgPd glass frit terminations had also proved to be unreliable due to bad planarity and high roughness of such terminals. An attempt to create filleted joints did not yield any significant improvement because of AgNP paste shrinkage during sintering process. Figure 7 demonstrates the typical detachment due to shrinkage.

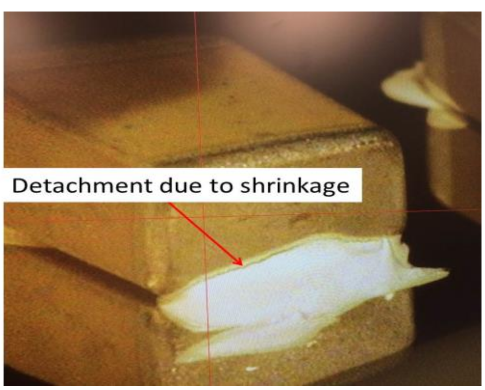


Figure 7. Image of an 1812 capacitor having AgPd glass frit terminals with a detachment of the AgNP joint

D. Durability tests

During thermal shocks from 35°C to 350°C, cracks in AgNP joints appeared after 50 shocks. A joint with cracks is shown in Figure. 8. After 100 shocks, the cracks were widespread, but the shear strength was 8MPa, which was still within an acceptable range.

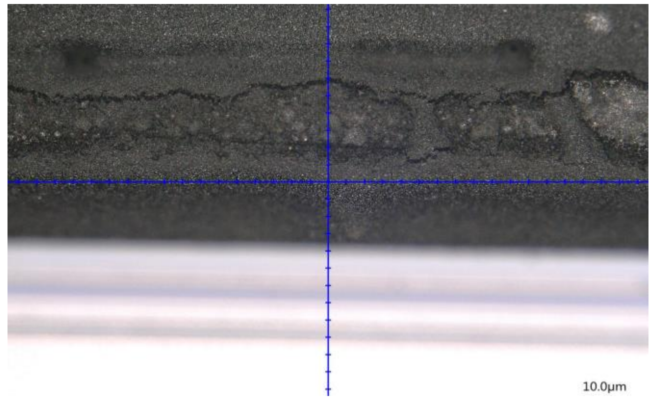


Figure 8. Cracks in AgNP joint after thermal shocks

30 thermal shocks from -35°C to 280°C with up to 350°C per minute ramp rate were completed to date. A shear test was conducted to evaluate the mechanical strength of the joints. The tested shear strength remained high—at 29Mpa. High-magnification visual inspection revealed no cracking after 30 shocks. Additional shock testing is ongoing to achieve at least 100 shocks.

Up-to-date results of the combined high-temperature aging and thermal cycling test are summarized in Table I. After 400 hours of aging at 280°C and 50 slow cycles between -35°C and 280°C, the shear strength of samples on thick-film and thin-film substrates remain significantly above the defined failure criteria.

Table I. Combined thermal durability test results to date

Film Type	200h + 25cycles	400h + 50cycles	600h + 75cycles	800h + 100cycles
Ag thin	26Mpa	29Mpa	23MPa	22MPa
Au thick	>25MPa	>25MPa	10MPa	9.8MPa
AgPd thick	>25MPa	>25MPa	>25MPa	>25MPa

IV. Discussion

To understand the failure mechanism and change on shear strength with different substrates, cross sections of die attachments on different substrates were investigated under a laser scanning microscope.

A. AgNP assembly on thin-film substrates

As shown in Figure 9, after 100 hours aging at 280°C, silver from AgNP joint precipitated over the surface of the thin-film Au on the substrate and formed a 1μm-thick dense film of silver on the top of the gold thin-film. This precipitation, a surface diffusion of silver bonding interface ligaments over thin-film gold surface, is much faster than silver's ability to self-diffuse and compensate for the loss. Consequently, large void regions formed in the Ag-Ag interface. This situation corresponds to the low or near-zero shear strengths and to the sheared fracture surfaces having silver on the die and the substrate sides. Interestingly, the substrate side fracture surface retains very good planarity and could accept die placement once more. This time the sintering was Ag-to-Ag, with vastly superior joint quality and strength. This study suggests that if Ag sintering on Au thin-film is used for certain low-temperature applications then the above-mentioned failure mechanism can be used for die rework in manufacturing, prototyping, and debugging stages, a process otherwise nearly impossible with an Ag joint having a melting temperature of 961°C.

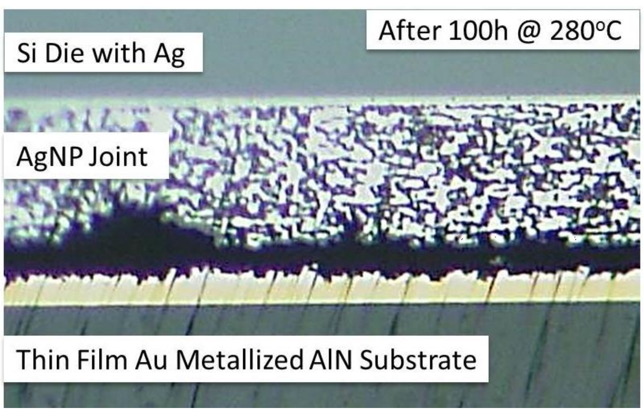


Figure 9. Cross section of Ag die attachment on thin-film Au substrate after 100 hours aging at 280°C

After high-temperature storage at 280°C for 100hr, the micro-structure of AgNP joint on thin-film silver showed uniform porous structure from the die to the substrate. Silver from the AgNP joint also precipitated over the surface of the thin-film Ag, forming a 2-μm dense film, but the ligaments between the porous structures and the dense Ag layer persisted, maintaining a reliable bond interface. While porosity remained roughly the same, the average pore size increased 2.2 times. This change in microstructure appears to be the cause of strength reduction shown in Figure 5.

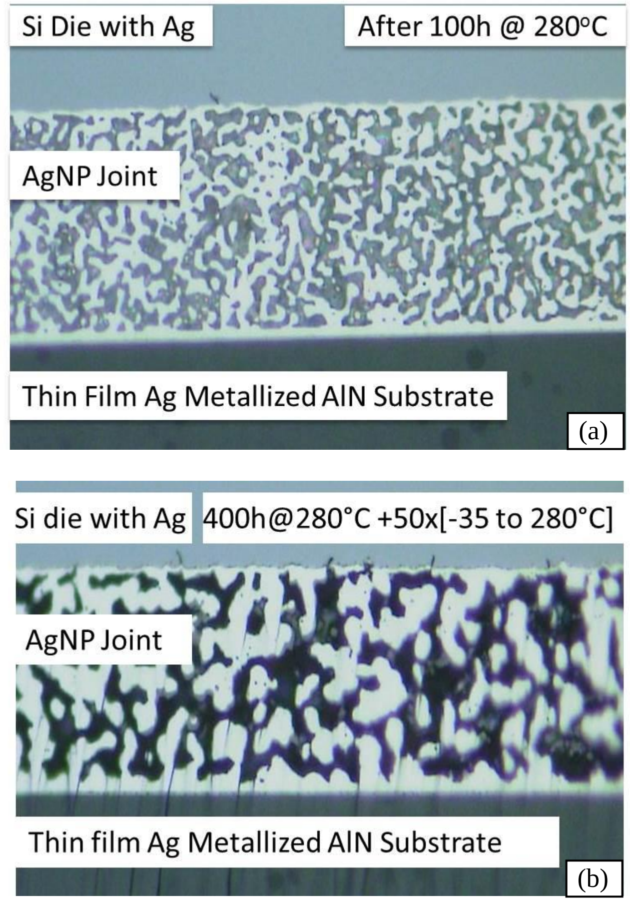
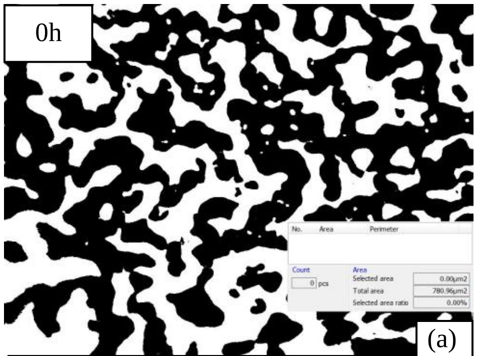


Figure 10. Cross sections of Ag die attachment on thin film Ag; (a) as-built; (b) after 100 hours aging at 280°C

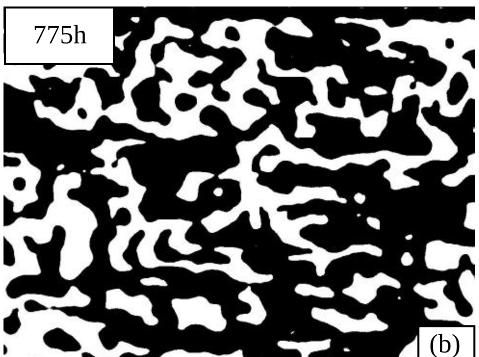
B. AgNP assembly on thick-film substrates

Cross sections of both die attachments on thick-film Au and AgPd were characterized for the microstructure of the joints to understand the failure mechanism.

Figure 11 compares AgNP microstructure change on thick-film Au as a function of aging time. The black islands are the pores in the cross section of the joint. The porosity is calculated as the ratio of black area to the total area, and the average pore size is the black area divided by the number of pores. After 775 hours of aging at 280°C, there is only a slight change in the porosity of the joint, while the pore size grows 2.4 times compared to the as-built value.



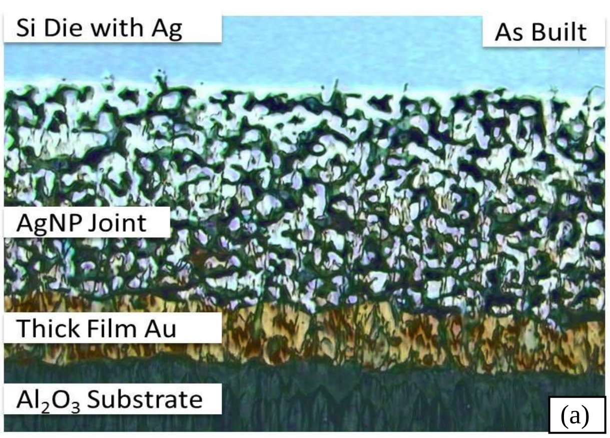
Porosity	Ave. Pore Size
42.81%	2.44μm^2



Porosity	Ave. Pore Size
40.17%	5.7μm^2

Figure 11 Porosity of the AgNP joint on thick-film Au; (a) as-built; (b) 775 hours aged at 280°C

Figure 12 is the laser scanning microscope image of as-built sample (a) and the 775-hour aged sample (b) on thick-film Au substrates. After 775 hours of aging, silver from the joint diffused into thick-film gold filling gaps. Meanwhile, gold from the thick film layer was also visible further inside the silver joint. Therefore, the bond at the interface of the AgNP joint and thick film gold is being reinforced by the mutual diffusion of gold and silver.



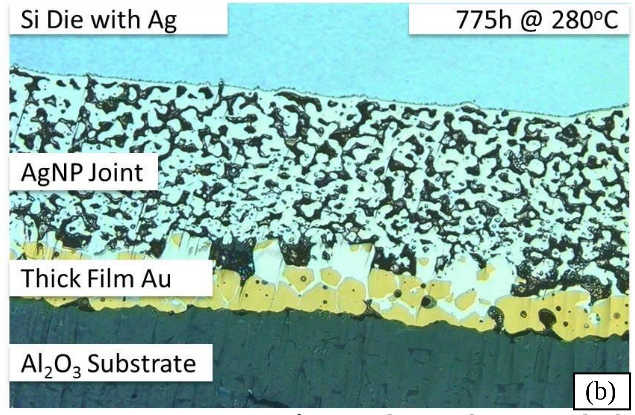
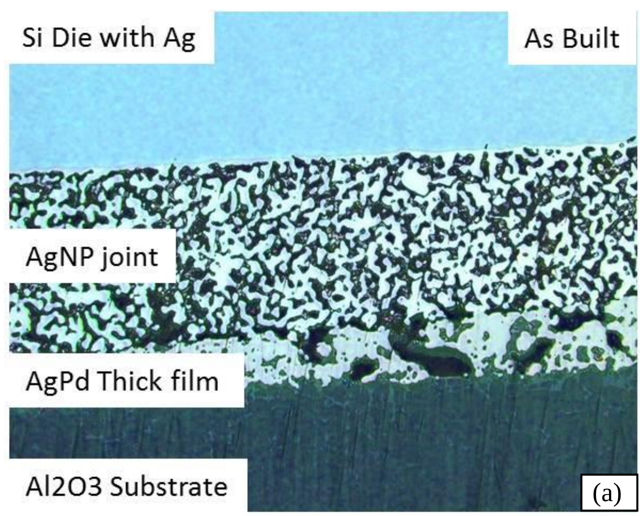


Figure 12. Cross sections of AgNP die attachment on thick-film Au (a) as-built; (b) 775 hours aged at 280°C

Figure 13 contains the scanning microscope images of an as-built sample (a), a sample after 20 cycles (b), and a sample after 900 hours of aging (c) on AgPd thick-film substrates. The porosity of the samples remained similar, and was estimated at 45%. The average pore size after 20 cycles increased 2.4 times, obtained the same level pore growth as the 900 hours aged samples, indicating that thermal cycling is a higher acceleration factor for pore growth process than aging. This change in microstructure is the cause of the shear strength reduction shown in Figure. 6. As evidenced by the images, there is no accumulation of dense silver at the interface of the silver joint and thick film that can be observed with high surface energy thin-films. The attachment interface of sintered silver joint to the thick-film remains porous over time.



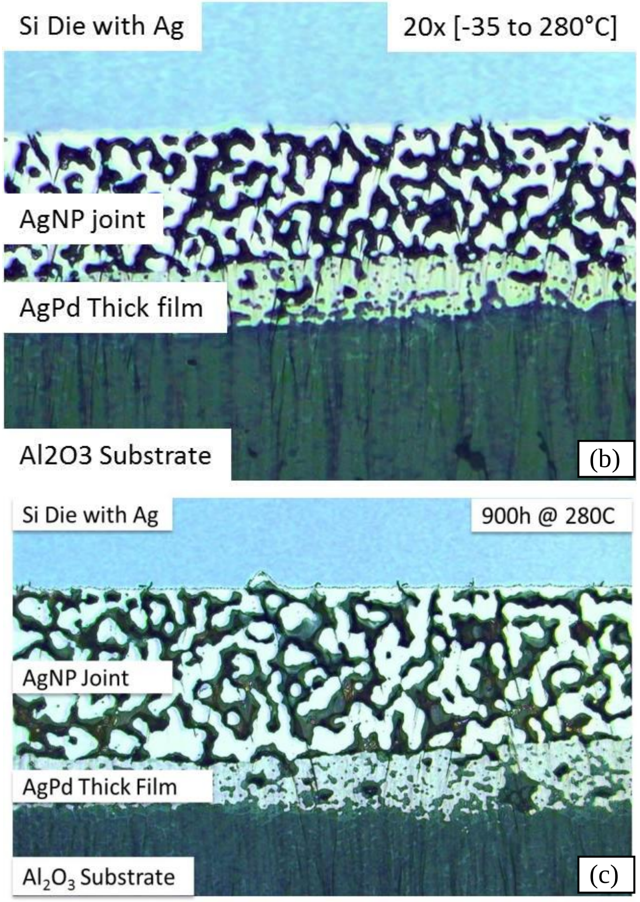


Figure 13. Cross-sections of AgNP die attachment on thick-film AgPd; (a) as-built; (b) after 20 cycles; (c) 900 hours aged at 280°C

Additional ongoing work related to use of sintered AgNP in high-temperature MCM assemblies investigates methods of electro-migration prevention, substrate attach reliability, and the impact of parylene coating.

V. Conclusions

This study evaluated pressure-less nano-silver attachment material for use in high-temperature multi-chip modules.

Following are the main conclusions drawn from the work. First, the pressure-less AgNP was found to be well compatible with high-volume batch assembly methods. Paste deposition and sintering have a wide processing window and high tolerance to the variability of manufacturing parameters. Second, the low joint strength on thin-film Au substrates at high temperature was immediately apparent which was attributed to rapid surface diffusion of silver ligaments over thin-film gold surface, leading to the formation of void regions. This failure mode can be utilized in die rework operations. Third, AgNP attachment of Ag back die on thin-film Ag, thick-film Au, and thick-film AgPd substrates is reliable at 280°C and has good resilience to thermal shocks. Notably, with high temperatures and mechanical loads the porous microstructure of sintered AgNP joints is continuously changing. Pore sizes are growing while porosity percent remains roughly unchanged. This leads to seemingly random realignment of pore locations and in turn, to location-dependent variation in shear strength.

Finally, attachment of SMT components with industry-standard chip construction using AgNP material was not reliable. To use the AgNP attachment for SMT components the geometry of their terminals needs to be similar to die geometry, i.e., full bottom surface terminal metallized with Ag or AgPd. Based on this research work, some recommendations for such modification of terminals geometry and metallization were made to components manufacturers operating in high-temperature segment of the market.

Acknowledgments

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