Evaluation of Au-Si Eutectic Die-Attach for Power Hermetic Packages in Space Applications

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Abstract

This study systematically evaluates the performance of Au-Si die-attach bonding through a combination of finite element analysis (FEA), cross-sectional material characterization, visual inspection, and mechanical testing. FEA thermal simulations demonstrate that replacing the resin thermoset die-attach with Au-Si bonding significantly enhances thermal performance across key metrics. In Device A, θ_{JA} decreased from 44 °C/W to 36 °C/W with either 14 µm or 7 µm Au-Si bond-line thickness (BLT). Device B exhibited a similar improvement, with θ_{JA} dropping from 26 °C/W to 20 °C/W. Notably, both Au-Si thicknesses delivered nearly identical thermal performance, indicating that thermal benefits plateau beyond a certain BLT. Mechanical FEA further reveals that Au-Si legs experience lower shear stresses than the resin thermoset, contributing to improved stress distribution. Die shear testing confirms robust mechanical integrity, with an average bond strength of 24.85 kg, which is significantly higher than the minimum specification of 2.5 kg. Cross-sectional SEM and EDX analyses confirm a dense die-attach layer with clean interfaces and Au-Si inter-diffusion. Despite these advantages, concerns arise from the higher normal stresses, approximately 250 MPa, observed in Au-Si joints compared to 90 MPa in the resin thermoset, which may increase the risk of interfacial delamination. Additionally, blister-like anomalies observed in Device B indicate silicon compatibility issues, highlighting the need for careful die-attach material selection, particularly in legacy die node designs.

Key words

Die-Attach, Eutectic Bonding, Hermetic Package, FEA

I. Introduction

Ceramic packages serve as a foundational technology in space-grade electronic systems, known for their excellent hermeticity, mechanical strength, and long-term durability under extreme environmental conditions. Their inherent resistance to ionizing radiation, along with their stability across wide temperature ranges and vacuum environments, makes them the preferred choice for mission-critical aerospace, defense, and satellite applications. In contrast, conventional organic packages often suffer from material degradation and reduced reliability under such harsh conditions, reinforcing the need for ceramic solutions to ensure long-term system functionality and survivability.

A key factor influencing the reliability and thermal performance of ceramic packages is the die-attach material, which serves both as the mechanical anchor and the thermal conduction path between the semiconductor die and the package header. In high-power applications, this interface must meet several stringent requirements. The die-attach material must exhibit low outgassing to prevent contamination and corrosion within the sealed package, provide high thermal conductivity for efficient heat dissipation, and possess sufficient mechanical compliance to withstand stress induced by thermal cycling. Additionally, it must be compatible with high-yield and repeatable manufacturing processes suitable for aerospace applications.

Resin-based thermoset adhesives are commonly used in ceramic packaging due to their ease of processing, low cure temperatures, and adequate adhesion. However, their low intrinsic thermal conductivity, typically around 1 W/m·K, limits their suitability for high-power applications. As power densities increase, these adhesives often become thermal bottlenecks, leading to elevated junction temperatures, degraded device performance, and accelerated failure rates. Another common die-attach material used in hermetic packaging is silver-filled glass. According to Nguyen [1], this material consists of silver and glass particles dispersed in an organic vehicle. A carefully controlled thermal profile is required to burn off the organic vehicle at the proper rate, allowing the residual silver and glass to form a bond between the die and the header. However, this process is difficult to control consistently in high-reliability applications.

To address these limitations, this study investigates gold-silicon (Au-Si) eutectic bonding as a high-performance alternative to adhesive-based die attach. Au-Si bonding offers several key advantages, including high thermal conductivity, excellent thermal stability, ultra-low outgassing, and strong metallurgical bonding. These characteristics make it particularly well-suited for power-intensive ceramic packages used in space environments. In this paper, we present a comparative evaluation of the thermal and mechanical performance of Au-Si eutectic bonding versus resin-based thermoset adhesives. Additionally, we examine practical assembly considerations and potential reliability concerns, such as die blistering, associated with the implementation of Au-Si eutectic bonding in production environments.

II. Mechanism of Au-Si Eutectic Bonding

Eutectic die bonding, often referred to as eutectic die attach, is a well-established technique in microelectronics, particularly for applications requiring enhanced thermal conductivity and hermetic reliability [2]. Among various eutectic systems, such as Au-Sn, Au-Ge, and Pb-S, the gold-silicon (Au-Si) system is widely used for attaching semiconductor dies in hermetic ceramic packages [3].

The Au-Si eutectic bonding mechanism is fundamentally governed by the alloying behavior between silicon and gold. While the melting points of pure gold and silicon are relatively high, 1064 °C and 1414 °C, respectively, the eutectic mixture of Au-Si melts at a significantly lower temperature of approximately 363 °C [4], as shown in Figure 1. This occurs at a eutectic composition of roughly 2.85 wt.% Si in Au (or 18.6 at. % Si and 81.4 at. % Au), as defined by the Au-Si phase diagram. This dramatically reduced melting temperature enables bonding under moderate process conditions, minimizing thermal stress on the silicon die and package substrate.

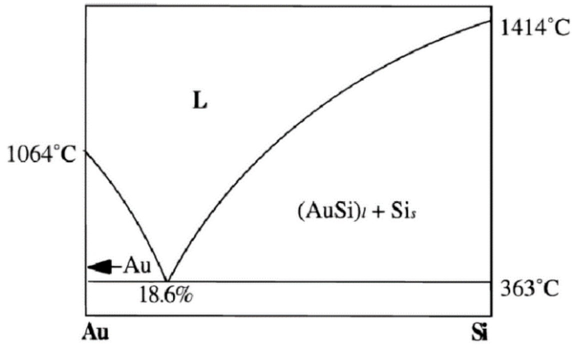


Figure 1. Phase diagram of gold and silicon [4].

The eutectic reaction begins with atomic contact between the gold and silicon surfaces. As the temperature is raised above the eutectic point, silicon atoms begin to diffuse into the gold layer. When the local composition at the interface reaches the eutectic ratio, a transient liquid phase form. This liquid phase accelerates mixing and diffusion between the two elements. Mechanical pressure is typically applied during this stage to ensure intimate contact and uniform bonding across the interface. Once sufficient interdiffusion occurs and the eutectic liquid is established, the assembly is cooled below the eutectic temperature, initiating solidification. This process often involves epitaxial growth of silicon from the melt and the formation of a polycrystalline gold matrix. In practical implementation, a thin gold-preform or plated layer is deposited on the package header, while the silicon die serves as the source of silicon [5]. Heating is typically applied via a hot plate or heated gas flow [6].

The inherent advantages of Au-Si eutectic bonding, its relatively low process temperature, strong metallurgical bond, and ultra-low outgassing, make it a compelling die-attach material candidate for high-reliability, space-grade ceramic packaging.

III. TEST VEHICLES AND ASSEMBLY

Two hermetic ceramic flat package (CFP) devices, shown in 3D view in Figure 2, were selected as test vehicles for this study. The key package attributes for both devices—Device A and Device B—are summarized in Table I, including die size, package size, peak temperature during die-attach, and the process atmosphere used.

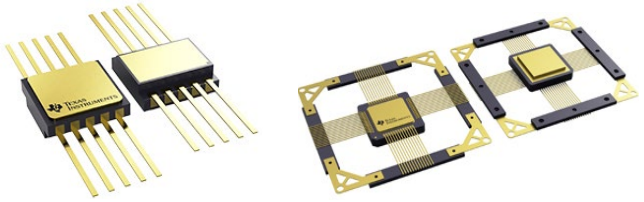


Figure 2. 3D views of 2 CFP packages as test vehicles.

As shown in Table I, Device A incorporates a 2.0 × 2.0 mm die in a 7 × 7 mm package, while Device B features a larger 2.6 × 2.6 mm die in a 14 × 14 mm package. Both devices were assembled using two different die-attach materials: a resin-based thermoset adhesive and Au-Si eutectic alloy. The peak temperature required for the thermoset adhesive process was 300 °C, whereas Au-Si eutectic bonding required a higher peak temperature of 420 °C. All bonding processes were conducted under a controlled atmosphere of high-purity nitrogen (N_2) to minimize oxidation and maintain bond integrity.

A key technique employed in the eutectic bonding process is scrubbing, which is essential to ensure a void-free, uniform bond interface. During scrubbing, a combination of vertical and lateral forces is applied to the die as it is placed onto the substrate. This typically involves micron-scale movement in alternating x and y directions repeated over several cycles. In some configurations, rotational scrubbing is also utilized [7]. Critical scrubbing parameters include amplitude, speed, and frequency in each direction. This dynamic motion enhances the wetting of the molten eutectic alloy, promotes uniform solder distribution, and aids atomic diffusion across the bonding interface, thereby improving bond quality [8].

Table I. Package Features of 2 Test Vehicles.

Device	Die-Attach Material	Die Size	Package Size	Peak Temperature	Process Atmosphere
Device A	Resin Thermoset	2.0 × 2.0 mm	7 × 7 mm	300ºC	High Purity N_2 Gas
	Au-Si Eutectic	2.0 × 2.0 mm	7 × 7 mm	420ºC	High Purity N_2 Gas
Device B	Resin Thermoset	2.6 × 2.6 mm	14 × 14 mm	300ºC	High Purity N_2 Gas
	Au-Si Eutectic	2.6 × 2.6 mm	14 × 14 mm	420ºC	High Purity N_2 Gas

Additionally, cover gas control is essential during the die-attach process. The bonding operation is carried out in an inert environment, typically high-purity nitrogen gas, to prevent oxidation of the bonding surfaces. Oxidation can impede metal diffusion and degrade the mechanical and thermal integrity of the bond. Maintaining an oxygen-free environment throughout the thermal cycle ensures consistent and reliable bonding performance.

According to [2], the minimum silicon layer thickness required to fully react with a given thickness of gold in a eutectic composition can be estimated using Equation (1). This relationship considers the weight percentage ratio of silicon to gold in the eutectic alloy, as well as the density of the respective materials. Specifically, the required silicon thickness is calculated as:

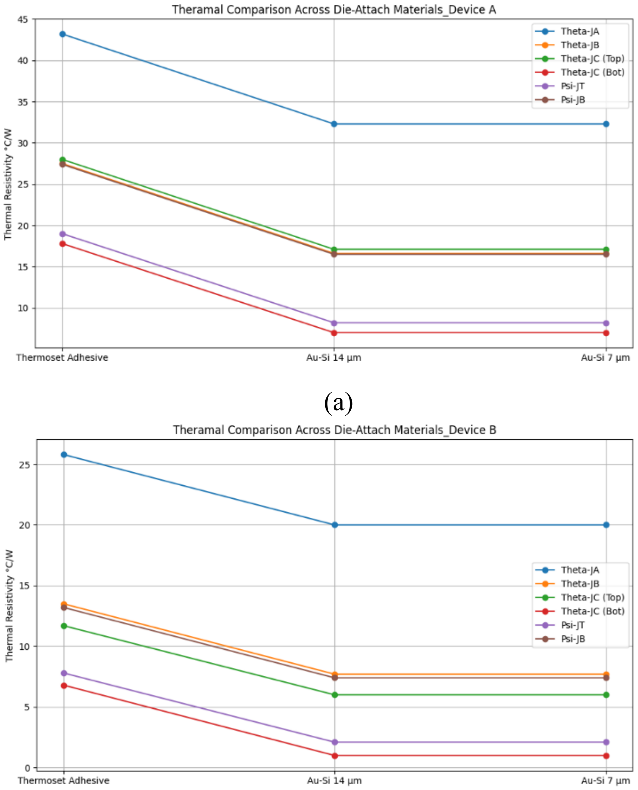
$$t_{Si} = \left(\frac{wt.\%\ Si}{wt.\%\ Au}\right) \frac{\rho_{Au}}{\rho_{Si}} t_{Au} \tag{1}$$

Substituting known values for the eutectic composition (1 wt.% Si to 99 wt.% Au), the densities of gold (19.3 g/cm³) and silicon (2.32 g/cm³), and a gold thickness of 25.4 µm, the minimum required silicon thickness is calculated to be 2.13 µm. In this study, the die thickness is approximately 280 µm, which is more than sufficient to fully react with the gold layer during eutectic bonding.

III. Thermal and Mechanical Simulation

To evaluate the thermal benefits of replacing thermoset adhesive with Au-Si eutectic bonding, thermal simulations were performed for both Device A and Device B. The objective was to assess the reduction in overall thermal resistance enabled by the use of high-conductivity die-attach materials. Simulations followed JEDEC standard printed circuit board (PCB) configurations with uniform power dissipation applied across the die area. It was assumed that all packages were mounted with formed leads soldered to the PCB. For the simulations, consistent material properties were used across all models. The thermoset adhesive was assigned a BLT of 40 µm and a thermal conductivity of 1 W/m·K, resulting in a thermal resistance per unit area of approximately 40.0 mm²·°C/W. In contrast, the Au-Si eutectic bond was modeled with either a 14 µm or 7 µm BLT, both having a much higher thermal conductivity of 200 W/m·K. This resulted in drastically lower thermal resistances per unit area—approximately 0.07 mm²·°C/W for the 14 µm case and 0.035 mm²·°C/W for the 7 µm case.

The simulated results are shown in Figures 3 and 4 for Device A and Device B, respectively. Multiple thermal resistance metrics were evaluated, including θ_{JA}, θ_{JB}, θ_{JC} (top and bottom), ψ_{JT}, and ψ_{JB}. In both devices, replacing the thermoset adhesive with Au-Si eutectic bonding led to a significant reduction in thermal resistance across all measured parameters. Notably, the simulations indicated that both 7 µm and 14 µm Au-Si layers produced nearly identical thermal performance. This suggests that beyond a certain threshold, further reduction in BLT offers minimal additional benefit due to already saturated thermal conductivity. For example, in Device A, θ_{JA} dropped from approximately 44 °C/W with thermoset adhesive to around 36 °C/W with either 14 µm or 7 µm Au-Si bonding. A similar trend was observed in Device B, where θ_{JA} improved from about 26 °C/W to about 20 °C/W, regardless of whether the Au-Si layer was 14 µm or 7 µm.



(a)

(b)

Figure 3. Thermal comparison of different die-attach materials in (a) device A and (b) device B.

These results demonstrate that switching to Au-Si eutectic bonding can greatly enhance heat dissipation in ceramic packages, with a thinner bonding layer offering a marginal advantage over slightly thicker ones when using a highly conductive material.

The mechanical simulation was conducted using a detailed finite element model, as shown in the Figure 4. A cross-sectional view of the meshed structure is illustrated, where a higher mesh density is applied to critical regions, including the die-attach layer and its interfaces with the die and header. This refinement ensures accurate stress calculation at regions prone to stress concentration.

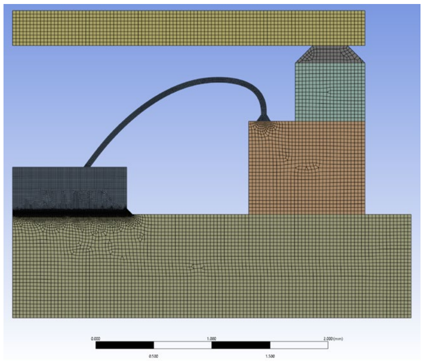
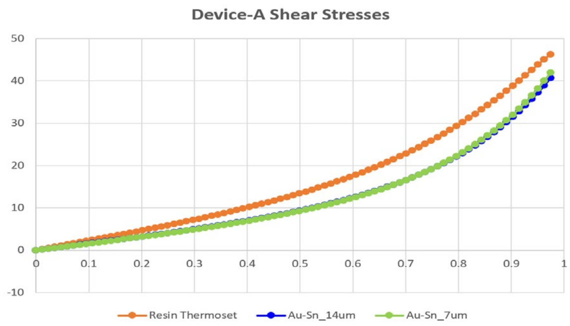
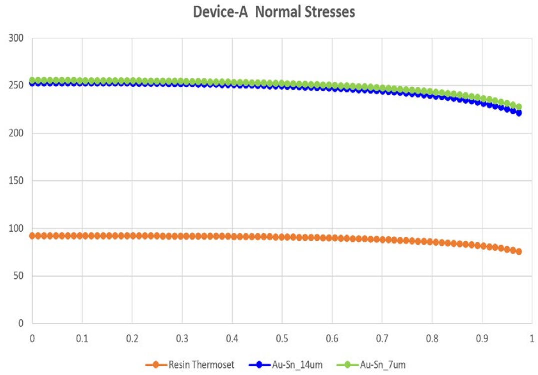


Figure 4. Finite Element Mesh of the Cross-Sectional Mechanical Model.

The finite element simulation results for both Device A and Device B show consistent mechanical behavior across different die-attach materials. For shear stress, the Au-Si layers with 7 µm and 14 µm thicknesses exhibit nearly identical performance in both devices, suggesting that reducing the Au-Si thickness does not compromise shear integrity. In contrast, the resin thermoset consistently shows higher shear stress accumulation. However, in terms of normal stress, both devices show that the Au-Si layers exhibit significantly higher values (around 250 MPa) compared to the resin thermoset at approximately 90 MPa. While this indicates a stiffer interconnect with Au-Si, it also raises concern about stress concentration at the interfaces, which could increase the risk of delamination or cracking under thermal or mechanical fatigue. Therefore, the higher normal stress in Au-Si joints must be carefully managed in reliability-critical applications.

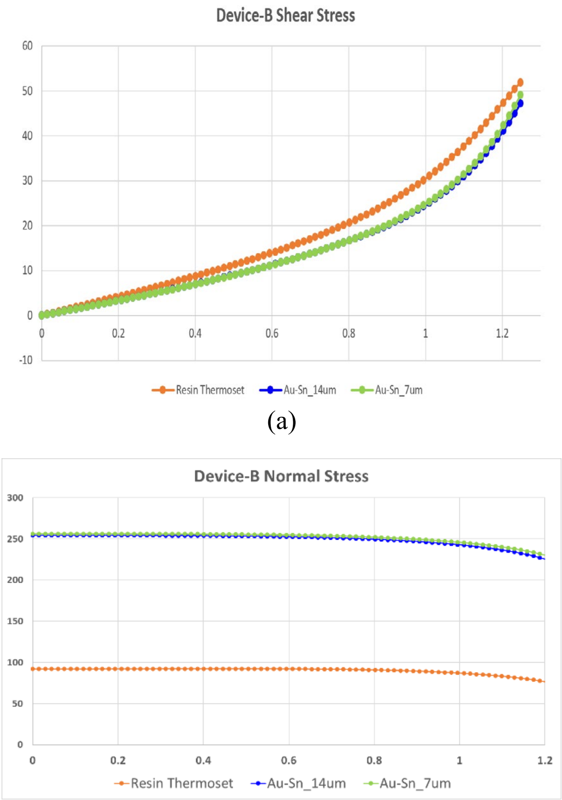


(a)



(b)

Figure 5. Comparison of (a) shear stresses, and (b) normal stresses in Device-A.



(a)

(b)

Figure 6. Comparison of (a) shear stresses, and (b) normal stresses in Device-B.

IV. Die-Attach Inspection

Visual inspection was performed on both Device A and Device B using bright field imaging and Nomarski differential interference contrast (DIC) techniques. The bright field method provides standard optical contrast based on reflectivity differences, while Nomarski imaging enhances surface topography contrast, making it especially useful for detecting subtle height variations and blistering effects across the die surface.

As shown in Figure 7, Device A exhibited no visible anomalies under either imaging technique, indicating a uniform and defect-free die top surface. In contrast, Device B revealed multiple irregularly shaped anomalies under both bright field and Nomarski observations, as highlighted in Figure 8. These anomalies resemble die blistering, typically characterized by void-like bubble structures within the aluminum layer and partially elevated features across the metallized surface. Such blistering commonly arises during high-temperature annealing processes (e.g., >400 °C) and may be attributed to suboptimal metallization design, including layer thickness, metal type, or geometric layout. Additionally, process variations during wafer-level fabrication, especially in legacy silicon nodes, can contribute to this phenomenon. The presence of these anomalies indicates a fundamental compatibility concern between the Au-Si die-attach process and the silicon used in Device B.

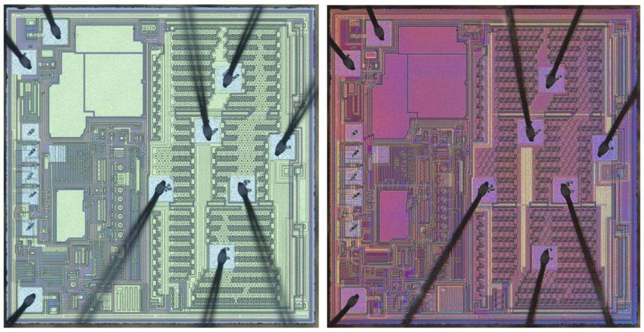

(a) (b)

Figure 7. Visual inspection on device A: (a) bright field image, and (b) Nomarski.

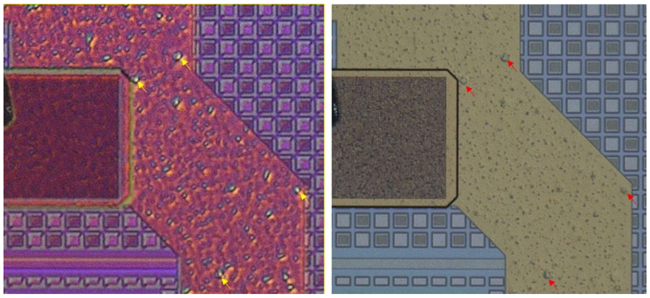

(a) (b)

Figure 8. Visual inspection on device B: (a) bright field image, and (b) Nomarski.

To further evaluate the die-attach integrity, shear testing was conducted on five sample units of Device A, which features a smaller die size. The average die shear strength was measured at 24.85 kg, significantly exceeding the minimum specification of 2.5 kg. This confirms robust adhesion and mechanical reliability of the Au-Si die-attach joint. Figure 9 presents the cross-sectional SEM image of the die-attach layer, clearly revealing a dense eutectic microstructure between the silicon die and the bottom header carrier. The interfaces are well-bonded without evidence of delamination or voiding near critical contact zones. Energy-dispersive X-ray (EDX) analysis, also shown in Figure 9, provides compositional mapping across the vertical cross-section. The elemental profiles confirm the presence of distinct layers: a silicon-rich region at the top, a well-defined Au-Si intermetallic zone in the middle, and a Nickel base surface finish layer at the bottom. Au-Si interdiffusion is clearly observed, further supporting the conclusion of a clean and well-controlled die-attach process.

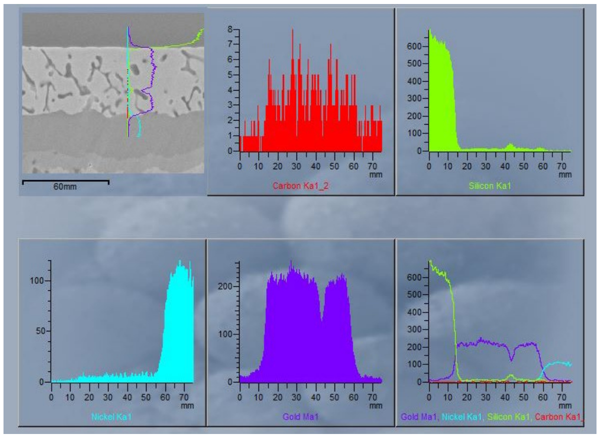


Figure 9. EDX analysis for cross-sectional view.

V. Summary

This study investigates the performance of Au-Si eutectic die-attach bonding in power ceramic packages designed for space applications. Through finite element analysis, thermal simulations show that Au-Si bonding significantly reduces thermal resistance compared to resin thermoset, enhancing heat dissipation. Mechanical FEA reveals lower shear stresses on Au-Si joints, and die shear testing confirms excellent bond strength. Cross-sectional SEM and EDX analyses validate a well-distributed eutectic bonding layer with clean interfaces. However, higher normal stresses and blister-like anomalies observed in certain devices raise concerns about compatibility with legacy silicon nodes. The findings highlight both the thermal and mechanical advantages of Au-Si bonding and the critical importance of material-process compatibility in high-reliability aerospace applications.

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