Thermal and Bonding Strength Evaluation of Die Attach Materials for Power Module Packaging

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***Abstract*— Die bonding materials are critical in power module packaging, as their ability to withstand the high temperatures generated during device operation directly impacts performance and longevity in real-world applications. Pressure-less soldering and sintering techniques are often preferred due to their simplified processes and lower equipment requirements. However, pressure-less sintering can result in suboptimal bonding strength between the semiconductor die and the Direct Bonded Copper (DBC) substrate, limiting its effectiveness in harsh environmental conditions. This paper investigates the influence of different die attachment materials and methods on power module packaging. Finite Element Analysis (FEA) models are used to analyze the thermal resistances of the die attachment materials. Shear tests were conducted to compare the bonding strength of various materials, including conventional solder preforms (Pb95Sn5), gold-tin alloy (Au80Sn20), silver paste (pressure and pressure-less processes), and silver preforms. Results from the shear tests indicate that pressure-assisted fabrication processes offer the highest bonding strength.**

Keywords— Pressure-less sintering, DBC, FEA, shear tests, thermal resistance, bonding strength

I. Introduction

In recent years, significant advancements have been made in wide band gap devices, driven by efforts toward miniaturization that have resulted in denser designs and expanded application possibilities, including multifunctional capabilities. The demand for high power density and the ability to withstand high temperatures in modern electronic devices continues to grow. These requirements necessitate the operation of devices under extreme conditions without compromising their mechanical integrity. This is particularly important for power module packages, which are utilized in applications such as motor drives, energy storage systems, electric vehicles, and renewable energy [1-2]. These power modules must operate at high power levels, often leading to elevated junction temperatures within the device [3]. At the interconnect level between the die and substrate, the die attach material plays a critical role in both heat dissipation and maintaining the mechanical integrity of the power module

Heat dissipation is an important feature of power devices or modules. The generation of heat within power module packages can induce material fatigue and significant thermomechanical stress. Consequently, it is imperative that the heat produced by the device is efficiently dissipated through the various layers of materials and bonded surfaces within the module. Die-attached technology has witnessed significant improvement in order to have improved heat transfer, reduced thermomechanical stress and increased lifetime of the power module. Silver sinter materials have garnered significant attention in recent years as interconnect materials for high-temperature power electronics packaging. This is due to silver's high melting point and its exceptional properties, including high thermal and electrical conductivity. The sintered silver die-attach method has demonstrated significantly superior thermal and electrical conductivity, along with greater reliability, compared to conventional soldering techniques, making it a preferred choice for applications requiring high efficiency and robust operational stability.

Silver sintering provides a more reliable method for die attachment bonding, forming interconnects at relatively low temperatures while ensuring excellent bonding strength and structural integrity. Pressure-less methods are desired and are on the verge of being used in the sintering process today. However, the strength of the pressure-less sintered interconnects is not yet sufficient for applications with high thermomechanical load [4-5]. Hence pressured sintering is done for reliable die attachment bonding [6-7]. The ongoing research in this area focuses on enhancing the properties of pressure-less sintering to make it a more viable alternative, aiming to achieve the reliability and durability required for high-performance power electronics.

This paper explores the impact of various die-attach materials on the performance and reliability of power modules, using conventional solder preform (Pb95Sn5), gold-tin preform (Au80Sn20), silver paste (both pressured and pressure-less), and silver preform. The study provides a systematic evaluation of each material's performance, focusing on their influence on the overall functionality and durability of power modules. Scanning Acoustic Microscopy (SAM) is utilized to investigate the microscopic structure of the bonding layers, offering insights into potential defects and voids. To assess the mechanical integrity, shear tests are conducted, analyzing the bonding strength of the different materials under various conditions. Additionally, the thermal resistance of the structures is evaluated using a Finite Element Analysis (FEA) model, quantifying the impact of each bonding material on heat dissipation. The findings from this study contribute to a deeper understanding of how die-attach materials affect the thermal management and mechanical reliability of power modules, which is crucial for advancing the design of high-performance electronic systems.

II. Importance of Packaging Materials

Currently, significant efforts are directed towards developing highly efficient cooling systems for heat removal in power electronics, optoelectronics, and telecommunication systems. However, the advancement of electronic components and microsystems capable of operating at high temperatures could enable designers to eliminate or

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significantly reduce the need for the costly and bulky cooling systems presently required to protect electronics in extreme environments [11]. As a result, packaging assumes a critical role in the development of wide band-gap devices.

In high-temperature power devices, numerous packaging processes are influenced by the transition to these advanced technologies. The materials used in packaging must not only withstand elevated operating temperatures but also provide reliable mechanical support and protection for the chip or device within the package. Achieving this requires a careful selection of materials to minimize thermal mismatch, considering the wide temperature range and the inherent stiffness of die-attach materials that must endure such conditions [12]. In addition to thermal stability, these materials must exhibit high electrical and thermal conductivity to ensure efficient heat dissipation and maintain electrical integrity under stress. The choice of encapsulants, substrates, and interconnect materials becomes increasingly critical, as they must be capable of withstanding not only the thermal expansion but also the mechanical stresses induced by repeated thermal cycling. Proper material selection is essential to prevent delamination, cracking, or other forms of mechanical failure that could compromise the reliability and longevity of the device. As power devices continue to evolve, the development of advanced packaging solutions will play a pivotal role in enabling their deployment in harsh environments.

III. Thermal Resistance Analysis via FEA Model

Sample structure used to develop the Finite Element Analysis (FEA) model is shown in Fig. 1. The FEA modeling was conducted based on the material properties listed in Table 1, with all parameters sourced from the respective material datasheets. To simulate the junction temperature under forced liquid cooling conditions, a heat transfer coefficient of 10 kW/m²·K was applied. The chip's power loss was set at 50 W to generate heat within the samples.

Fig. 2 compares the steady-state junction temperatures of the samples, each utilizing a different bonding layer. The figure reveals that the choice of bonding material influences thermal performance. Specifically, the sample with a silver preform, which has the highest thermal conductivity, exhibited the lowest junction temperature. In contrast, the sample with a Pb95Sn5 preform, having the lowest thermal conductivity, showed the highest junction temperature. This relationship between thermal conductivity and junction temperature is further reflected in the thermal resistance of the samples.

As shown in Fig. 3, the silver preform not only achieves a lower junction temperature but also exhibits a thermal resistance approximately 2.5% lower than that of the Pb95Sn5 preform, which has the highest thermal resistance. These findings underscore the critical importance of selecting appropriate bonding materials in power modules, as they directly impact both the thermal management and overall reliability of the system. The study highlights the potential for silver-based materials to enhance the efficiency and performance of high-power electronic devices by reducing thermal resistance and improving heat dissipation.

Table I: Bonding material parameters used in the FEA model

Name	Density (kg/m³)	Heat capacity (J/(kg·K))	Thermal Conductivity (W/(m·K))
Pb95Sn5 preform	7380	233	33
Silver paste [8]	8600	235	140
Silver preform	8600	235	200
Au80Sn20 preform [9]	14510	150	55

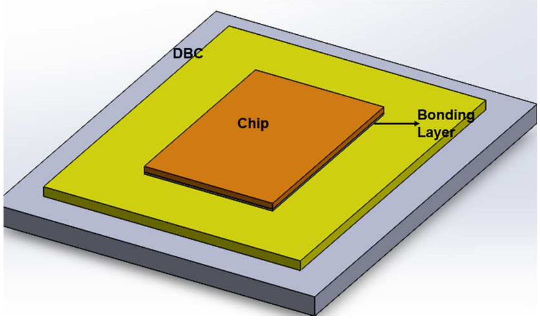
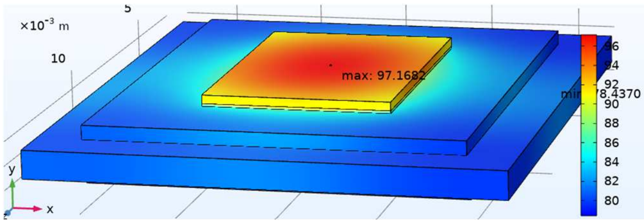


Fig. 1: Structure of the sample



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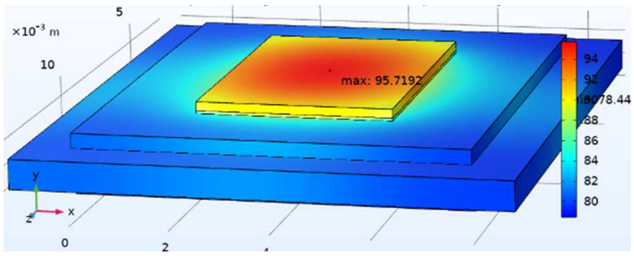

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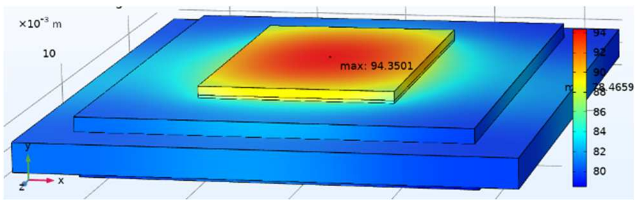

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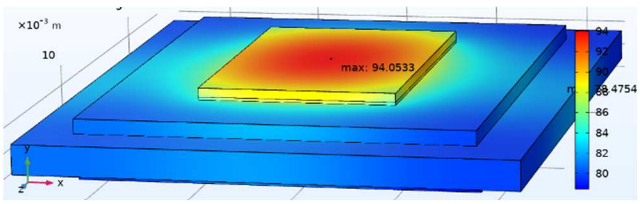

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Fig. 2: Steady state junction temperature comparison using different bonding layer, a) Pb95Sn5, b) Au80Sn20, c) Silver paste, d) Silver preform

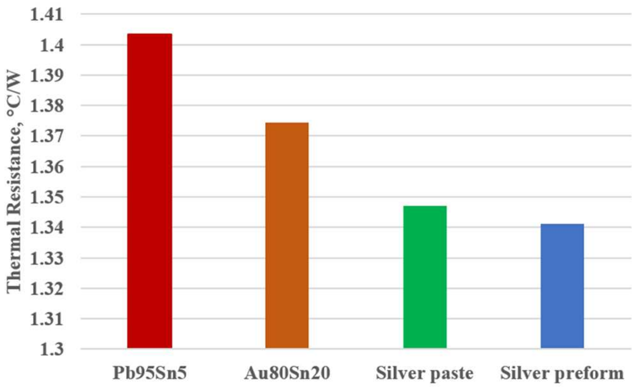


Fig. 3: Thermal resistance comparison using different bonding materials

IV. Experimental Analysis for Die Attach Strength

A series of samples were developed using dummy chips and DBC substrates bonded with various bonding materials to evaluate their mechanical performance. An experimental setup was established to perform experimental analysis on the bonding integrity of these materials. The samples were prepared by bonding a dummy chip with gold coating (10 mm x 10 mm x 0.525 mm) to a substrate also coated with gold (16 mm x 15 mm x 1.5 mm). The bonding materials used included Pb95Sn5 preform, Au80Sn20 preform, silver paste (both pressured and pressure-less), and silver preform.

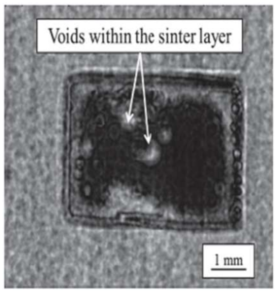
For the pressure-less samples, including Pb95Sn5 preform, Au80Sn20 preform, and pressure-less silver paste, a vacuum reflow oven (SST oven) was utilized, as shown in Fig. 4(a). Samples requiring high pressure were prepared using a hotplate, as shown in Fig. 4(b), which generates heat according to the specifications in the material datasheets for bonding and sintering processes. Additionally, a Mark-10 ES20 pressure machine was employed to apply a constant pressure of 59 kPa during the fabrication of the pressured silver paste samples. This ensured effective bonding of the layers, minimizing voids in the bonding layer, which was validated by Scanning Acoustic Microscopy (SAM) images in Fig. 5. The SAM images clearly show that pressured sintering produces void-free bonding layers, while pressure-less sintering is more susceptible to void formation. The reduction of voids through pressured sintering is crucial, as voids can significantly weaken the bonding strength.

(a)

(b)

Fig. 4: Fabrication setup, a) Vacuum reflow oven for pressure less fabrication, b) Hotplate and ES 20 for pressured fabrication

(a)

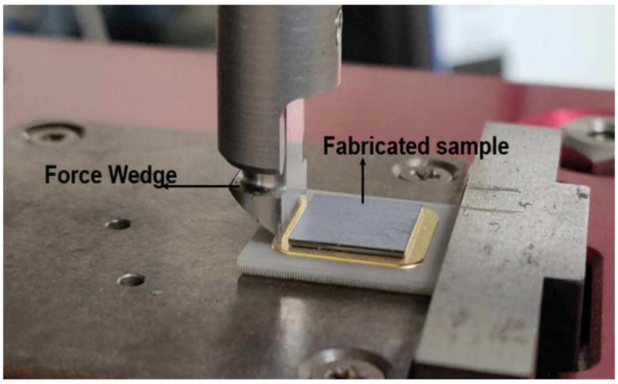


(b)

Fig. 5: Differences in bonding quality a) Bonding layer with silver paste having a constant pressure of 59 kPa. b) Bonding layer with pressure-less silver paste having voids within the silver-sinter layer [10]

The shear testing setup, depicted in Fig. 6, was utilized to evaluate the mechanical strength of the bonding layers in the prepared samples. The force required to break each bonding layer is detailed in Table II. Notably, the bonding layer formed using pressured silver paste demonstrated exceptional strength, remaining unbreakable under a force of 1000 N. This highlights the superior bonding capability and mechanical robustness of this material under high-stress conditions. However, samples bonded with silver preform under high pressure (5 MPa) exhibited die fracture, revealing the material's limitations when subjected to extreme mechanical loads. This suggests that while silver preform offers excellent thermal properties, its mechanical resilience is compromised under certain conditions, indicating a trade-off between thermal and mechanical performance. The results of the shear test, illustrated in Fig. 7, provide deeper insights into the comparative performance of each bonding material. From the figure it can be observed that with Pb95Sn5 and pressure-less silver sintering, there was metallization between both the DBC and the dummy chip. There was no issue with the metallization of the bonding material with the chip. The samples prepared with Au80Sn20 preform and pressured silver sintering did not break under 1000 N of force, show casing superior bonding strength. From Fig. 7 (c), it can be observed that chip connected with silver preform has high bonding strength, but due to high pressure involved in the fabrication process, the chip, undergoes die fracture.

(a)

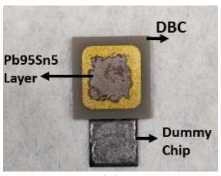


(b)

Fig. 6: Shear test setup, a) Dage DS 100 model used for shear test, b) Dage DS 100 being used to shear a sample

Table II: Shear test results

Name	Area (mm^2)	Shear force (N)
Pb95Sn5	100	81
Au80Sn20	100	>992 (unbroken)
Pressured Silver paste	100	>992 (unbroken)
Pressure less Silver paste	100	556
Silver preform	100	420 (Die fracture)



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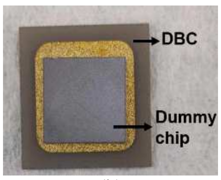

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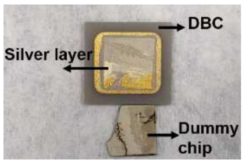

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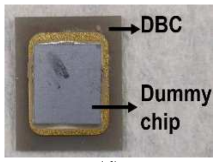

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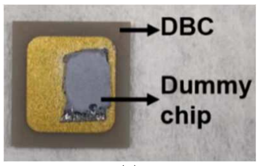

(e)

Fig. 7: Shear test results a) Pb95Sn5 preform sample, b) Au80Sn20 preform sample, c) Pressure less silver sintered sample, d) Pressured silver sintered sample, e) Silver preform sintered sample

V. Conclusion

This study investigates the impact of various bonding materials on the thermal and mechanical performance of power module assemblies. Using Finite Element Analysis (FEA), it has been demonstrated that the efficiency of heat dissipation is significantly influenced by the thermal conductivity of the bonding material. Higher thermal conductivity materials, such as silver preform, facilitate more effective heat removal, thereby reducing junction temperatures. Scanning Acoustic Microscopy (SAM) was employed to validate the integrity of the bonding layers, particularly in samples fabricated using pressured sintering techniques. The SAM results confirmed the absence of voids in the bonding layers of these pressured samples, thereby underscoring the reliability and effectiveness of the pressured fabrication process in ensuring robust interconnects. Additionally, shear tests were conducted on samples with dummy chips to compare the mechanical strength of the bonding layers. The results reveal that bonding layers created with pressured silver paste exhibit exceptional shear strength, withstanding forces up to 1000 N without failure. However, due to high pressure (5 MPa), the samples prepared by silver preform underwent die fracture. These findings highlight the critical role of bonding material selection in optimizing both thermal management and mechanical reliability in power modules. The study provides valuable insights for the development of high-performance electronic devices, where both efficient heat dissipation and strong, void-free interconnects are essential.

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