Emadi, F.; Liu, S.; Klami, Anton; Tiwary, N.; Vuorinen, V.; Paulasto-Krockel, M.

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Low-temperature die attach for power components: Cu-Sn-In solid-liquid interdiffusion bonding

F. Emadi*, S. Liu*, A. Klami*, N. Tiwarya, V. Vuorinen, & M. Paulasto-Kröckel

*Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, PO Box 13340, FI-00076, Aalto, Finland
e-mail: fahimeh.emadi@aalto.fi and shenyi.liu@aalto.fi

Based on the finite element (FE) simulations done in this work, lowering the bonding temperature significantly decreases the bonding induced residual stresses. Therefore, low temperature Cu-Sn-In SLID process was utilized to bond Si to Si and Si to sapphire under various bonding conditions. The microstructural evolution and the (thermo-) mechanical properties of the joints were studied. The results showed that the Cu-Sn-In SLID bonds composed of a single Cu$_6$(Sn,In)$_5$ IMC phase with high joint strength. Furthermore, the hardness and Young’s modulus of Cu$_6$(Sn,In)$_5$ formed in the SLID bonding were measured to be slightly higher than that of binary Cu$_6$Sn$_5$.

1. Introduction

In recent years, power electronics devices have become more frequently used in different fields, such as hybrid-electric vehicles, renewable power systems, and HVDC transmission technology [1, 2, 3]. Moreover, the power densities in the power devices have increased to meet the demands of the different applications [4]. This leads to the development of wide bandgap (WBG) semiconductors such as SiC and GaN. With the usage of WBG semiconductors, power electronic devices can operate at higher temperatures and frequencies than Si-based devices. The increased temperature would require higher performance and reliability of the die attach [4]. Therefore, to better apply the advantages of the high-performance power components, alternative die-attach materials with the following characteristics are needed: 1) low bonding temperature to decrease the induced stresses and 2) efficient performance of high-temperature power devices under normal operating conditions. The low-temperature SLID bonding can typically be performed at a temperature close to 200°C or even below that [5], which means that the intrinsic stresses within the bond will be reduced compared to that at a higher temperature [6]. Additionally, the bond has a high melting point, even though it is formed at a low temperature. The interconnection material also has high electrical and thermal conductivity, and high mechanical strength [6]. However, reliability studies on the SLID bonds are still needed when applied to power semiconductors die attach [7, 8, 9]. Hence, this article aims to evaluate the feasibility of using SLID bonding as a die-attach method for power components. Firstly, the FE simulation was accomplished. Then, the low-temperature Cu-Sn-In SLID system was utilized to bond Si to Si and Si to sapphire under various bonding conditions. The microstructures in the bonds are analysed from cross-sectional samples. Furthermore, a group of samples are also aged with thermal cycling to study long-term reliability. The mechanical properties of the bonds, such as Young’s modulus, were determined by nanoindentation.

2. Materials & Methods

FE simulations were performed to study the impact of lower bonding temperature on the thermomechanical stresses formed in the SLID bonds. The bonding temperatures evaluated were 300 °C, 200 °C and 150 °C. For 300 °C, Cu$_3$Sn intermetallic (IMC) layer was
incorporated. For 200 °C and 150 °C, Cu₆Sn₅ IMC layer was incorporated. The bonding methodology was adopted as reported in our earlier publication [10]. The Young’s modulus and Poisson’s ratio of Cu₃Sn and Cu₆Sn₅ were incorporated from [11]. The initial yield stress and isotropic tangent modulus for Cu were set to 250 MPa and 2 GPa, respectively. All other material parameters were incorporated as the default values available from COMSOL library.

Figure 1 (a -b) shows the schematic of the model and diagonal cut plane across which stresses are evaluated. The line graphs are evaluated along the cut lines shown in Figure 1 (b), blue – at the middle of the plane and green – 5 µm away from the corner. Figure 1 (c-e) shows the simulation results of von-Mises stress for Si to Si bonded at different temperatures. It could be clearly seen that the stress in the bonds reduces significantly with lower bonding temperatures.

A 60nm-thick TiW adhesion layer was sputtered on silicon and sapphire wafers, followed by a 100nm-thick copper seed layer sputtering. Then 4µm of copper and 2µm of tin were electroplated utilizing NB Semi plate Cu 100 bath and NB Semi plate Sn 100 solution from NB technologies, respectively. The Si and sapphire wafers were cut into 5 × 5 mm and 10 × 10 pieces, respectively. In-contact Si to Si and Si to sapphire chips were placed in a metal holder to apply a specific bonding force. Then Si to Si samples and sapphire samples were bonded in an air muffle furnace at 200°C for 1,2, and 4h and 150°C for 2h, and at 200°C for 2h, respectively. The microstructure and (thermo-) mechanical properties of the samples were characterized using following Analysis methods: 1) SEM-EDX analysis, 2) Thermal Cycling test (100 cycles :15 minutes at -40 °C, 15 minutes at 125 °C), 3) Tensile Test, and 4) Nanoindentation test.

3. Results and discussion

3.1 Microstructural evolution

When studying the cross-sectional micrographs from Si to Si and Si to sapphire SLID samples bonded at various bonding conditions (bonding temperature and time) it was revealed that all SLID joints composed of a single Cu₆(Sn,In)₅ IMC layer (Figure 2 a-e). The results indicate that In stabilized the Cu₆Sn₅ phase which is in a good agreement with previous reports [11]. Single phase joints can be beneficial for the packaging of the devices that demands
reduction in the induced stresses and voids formation during bonding as Cu$_6$Sn$_5$ transformation to Cu$_3$Sn cause volumetric change and void formation.

3.2 Mechanical characterization

Figure 3 shows the bond strengths for different samples. The results were averaged from at least 3 samples for each test condition. Results indicated that most of the samples did not break from the bond in the tensile tests. Instead, the samples broke from the glue, or the sample holder failed to hold the sample properly which usually happened by applying force around 130N (which is considered as capped force in this work). Therefore, the strength of the unbroken samples was above these limits and the limits could be considered as the minimum strength of the samples. Based on the tensile strength measurements, all the samples showed tensile strength values above 5MPa. According to MIL-STD [13], the minimum strength required from the samples is 1.52 MPa. Hence, it can be concluded that the Cu-Sn-In SLID bonds exhibit high strength that fulfilled the minimum die attach strength requirement. The broken samples after tensile tests were evaluated by SEM-EDX to study the fractures’ positions,

![Figure 2. Cross-sectional BSE micrographs of (a) Si- sapphire bonded at 200°C for 2h, (b) Si-Si SLID bonded at 200°C for 2h, (c) 200°C for 1h, (d) 200°C for 4h, and (e) 150°C for 2h.](image)

![Figure 3. Average bond strengths of different as-bonded samples: Si to Si SLID bonded at 200°C for 1h (Si1), 2h (Si2), 4h (Si4), at 150°C for 2h (SiL), and Si to Sapphire SLID bonded at 200°C for 2h (Sa2).](image)

![Figure 4. Tensile fracture surface of a Si-Si SLID bonded at 200 °C for 2 h (a) top silicon fracture surface, (b) bottom silicon fracture surface, and (c) an illustration of fracture path.](image)
which revealed the weak areas in joints. Figure 4 shows the fracture surface of Si to Si SLID bonded at 200°C for 2h (other SLID samples exhibited almost same fracture surfaces). The SEM-EDX analysis revealed that the fracture path was as follows: at the TiW-Cu6(Sn,In)5 interface, at the TiW-Cu interface, inside Si, and inside the unreacted Sn/In layer (Figure 4c). This indicated that the Cu-TiW and IMC-TiW interfaces are the weak areas in the joint, however, as mentioned above, the SLID samples showed strength higher values than what a die attach required to be reliable.

The Young’s modulus and hardness of the Cu6(Sn,In)5 and Cu6Sn5 formed in Cu-Sn-In and Cu-Sn SLID systems, respectively, were calculated via nanoindentation test as follows: 149±4 (GPa) and 9.2±0.7 (GPa), and 114±1 (GPa) and 6.7±0.4 (GPa), respectively. However, the hardness and Young’s modulus values for Cu6(Sn,In)5 are higher than Cu6Sn5; Cu6Sn5 showed slightly higher plasticity compared to Cu6(Sn,In)5 (by comparing the E/H values which are an indication of the plasticity for brittle materials [14]).

3.3 Thermal cycling test

Thermal cycling is a typical method for evaluating reliability and lifetime of joints in the electronic devices. Therefore, the microstructure and the tensile strength of samples (Si to Si and sapphire to Si SLID bonded samples) were examined after thermal cycling test (100 cycles :15 minutes at -40 °C, 15 minutes at 125 °C). Figure 5(a,b) shows the SEM micrographs of samples after thermal aging. As can be seen no new IMCs formed during the thermal cycling and the microstructures remained same as the as bonded samples. However, as there was still remained Sn/In in the system, the formation of the Cu6(Sn,In)5 was continued. The results indicated that the microstructure will not change during thermal cycling (at least for the tested cycles in the current work). No stresses will be induced to the system due to the phase transformation.

The comparison between the strengths of the joints before and after the thermal cycling test is shown in Figure 5. As can be seen, the strength of the samples after the thermal shock test also exceeded the minimum requirement from MIL-STD, even though the bond strength weakened in silicon-sapphire samples due to the CTE mismatch.

5. Conclusion

In Conclusion, Cu-Sn-In SLID bonded samples were composed of a single phase Cu6(Sn,In)5 and no Cu3Sn was detected in the bond line. The Cu-Sn-In SLID samples can be less prone to the void formation and induced stresses compared to the SAC soldered samples and Cu-Sn SLID samples as no phase transformation from Cu6Sn5 to Cu3Sn take place in Cu-Sn-In SLID systems. On the other hand, Cu-Sn-In SLID systems can be bonded at a temperature
as low as 150°C. Therefore, such low temperature can reduce the induced stresses during the bonding, which can be beneficial for high performance power applications. In addition, the mechanical characterization showed that SLID samples exhibited the strengths values above the minimum requirements for the die attach materials. It is important to mention that the strength of the samples fulfilled the minimum requirements even after the thermal cycling test carried in the current work. From the nanoindentation test, the hardness and Young’s modulus values of the Cu₆(Sn,In)₅ formed in the Cu-Sn-In SLID systems were higher than Cu₆Sn₅ which forms in Cu-Sn SLID system as well as SAC soldering.

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