

Improvement of SLID Bonding for Ni/Ni Joints in 3D-IC Packages and Power Modules through Ag₃Sn Intermetallic Interlayer

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Abstract - Solid liquid interdiffusion bonding (SLID) provides a promising technique for advanced packages. However, the uneven growth of intermetallic compounds (IMCs) in Ni/Ni joints often causes the appearance of a large number of voids, which degrade the bonding strength and electrical and thermal conductivities. An example of the application in the Si/Si wafer bonding of 3D-IC packages was shown in the SLID bonding of Ni/Sn/Ni between two Si substrates at 250 °C for 30 min, which resulted in the formation of many voids at the interface between Ni₃Sn₄ intermetallic compound layers and a shear strength of 13 MPa. An improved method through the employment of an innovative patented concept of dual-phase IMCs has been proposed to diminish the voids and increase the bonding strength. This technique uses an additional 2µm Ag thin film to be inserted into the Ni/Sn/Ni sandwich to form the Ni/Ag/Sn/Ni or Ni/Sn/Ag/Sn/Ni metal stacks. After SLID bonding, the interfacial reactions between Ag and Sn result in the appearance of Ag₃Sn IMCs filling the voids of the simultaneously formed scallop-like Ni₃Sn₄ IMCs to achieve a void-free interconnection. The average shear strength was drastically increased to 20 MPa. A similar example for the application in die attachment of power modules was also shown in the SLID bonding of Si/Ti/Ni/Ag/Sn with Au/Pd/Ni/Cu/Al₂O₃ DBC substrates at temperatures from 250 °C to 350 °C for 30 min to eliminate the interfacial voids and also obviously increase the bonding strengths.

Keywords: Solid liquid interdiffusion bonding, Ni/Ni joints, intermetallic compounds, bonding strength

1. Introduction

Solid liquid interdiffusion bonding (SLID) offers several technological advantages of the low-temperature bonding process and high-temperature application, which has been widely used in the fabrications of power modules, thermoelectric modules, high power LED packages, and 3D-IC packages [1]. For this bonding technique as demonstrated in Fig. 1, a low melting point (LT) thin film interlayer, usually Sn or In, is inserted between two metallic layers with higher melting point (HT) (i.e. Ag, Au, Cu, Co, or Ni) and heated above the melting point of LT-thin film interlayer. After the interfacial reactions, the liquid LT thin film reacts completely with the HT metallic layers and isothermally transfers into solid intermetallic compounds (IMCs), which possess a much higher melting temperature than that of the original LT interlayer. Several binary systems, such as Au-Sn [2-5], Cu-Sn [5-7], and Ag-Sn [8] are commonly utilized options for reliable SLID bonding in microelectronic packaging. While resembling solder bonding in terms of operation temperature and IMC formation [9], SLID bonding has excellent thermal stability at temperatures far surpassing the bonding temperature [10, 11].

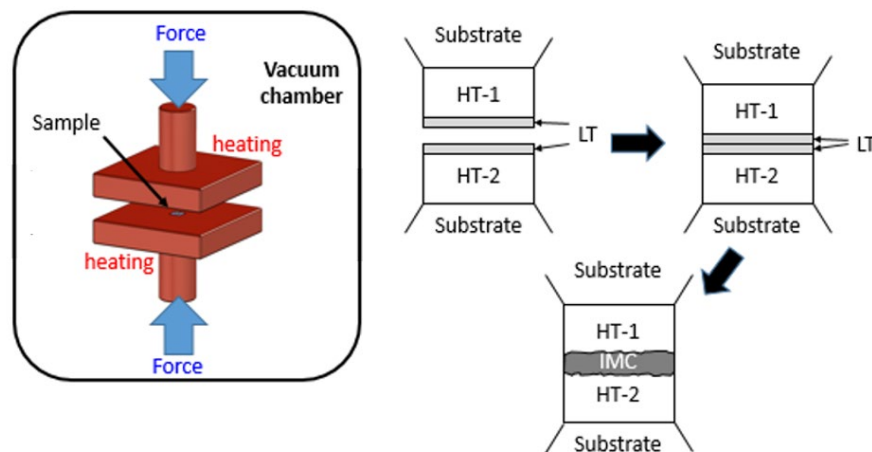


Fig. 1 The schematic diagram of the solid liquid interdiffusion bonding (SLID) process.

Nickel (Ni) and Ni-based alloys are often considered as excellent HT metals for reliable SLID bonding. Often, Ni has a very low dissolution rate at low temperatures, so only a thin layer of IMC will form in the Sn/Ni interface [12-14]. The interfacial reaction between Ni and Sn has been extensively studied, comprising 5 stable solid single phases: Ni (Sn), Ni-Sn, Ni₃Sn₂, Ni₃Sn₄, and Sn (Ni) [15, 16]. Yet, the formation of the Ni₃Sn₄ phase is well known to have deleterious effects on the long-term reliability of the Sn-Ni SLID bonds. In particular, Ni₃Sn₄ has been described in different morphologies, including scallop-like structure [17-19], whisker-like structure [20], facet structure [14, 19], and even continuous thin layer [19, 21]. However, the growth of scalloped Ni₃Sn₄ grains causes the appearance of voids in the SLID joints [15]. The cracks propagate along the bonding interface to connect the Ni₃Sn₄ grains. Particularly in high-powered electronic packaging, voids in the SLID joints can reduce the reliability due to the significant reduction of heat dissipation and contacted cross-sectional area.

As the significance of the Sn-Ni SLID bonding in advanced microelectronic packaging technology has arisen, there is a particular need to solve the void formation issues by the interfacial reaction of Sn/Ni. Chang et al. proposed a patent that the presence of dual intermetallic phases (Ag₃Sn and Ni₃Sn₄) can effectively solve the void problems in the Ni/Sn solder joints [22, 23]. Such an advantageous effect of Ag₃Sn intermetallic layer to diminish the interfacial voids of Ni/Sn/Ni SLID bonded Ni/Ni joints has also been confirmed by Chuang et al. [24], Yu et al. [25], and Chu et al. [26]. In the present study, the beneficial effects of void elimination and bonding enhancement through the existence of Ag₃Sn intermetallic phase in the Ni/Ni joints for the Si/Si wafer bonding in 3D-IC packages and die attachment of Si/DBC ceramic substrate in power modules are investigated. This paper also aims to clarify the mechanism of Ag₃Sn filling in the Ni/Sn/Ni interfacial reaction system during the SLID bonding process.

2. Experimental

To investigate the interfacial reaction and the microstructural evolution of the SLID bonding Ni-Sn system, (100)-oriented p-type silicon (Si) wafers are metallized with multi-thin films of Cr/Cu/Ni/Sn, Cr/Cu/Ag, and Cr/Cu/Ni/Sn/Ag as shown in Fig. 2(a), 3(a) and 4(a). To perform the SLID bonding process for a simulated 3D-IC packaging structure, the backside metallized Si chips are sandwiched and bonded together at 250 °C for 30 minutes under 20 MPa in a vacuum hot press furnace.

In another study to evaluate the SLID bonding of Si chips with direct bonding copper (DBC) alumina substrates for power modules, the Si wafers were metallized with Ti/Ni/Ag and Ti/Ni/Ag/Sn thin films. In addition, the Cu conductive layer on DBC ceramic substrates was surface finished with Ni/Pd/Au multilayers. The SLID bonding processes were conducted at various temperatures ranging from 250 °C to 350 °C for 30 min.

After SLID bonding, the specimens are sectioned and mounted in an epoxy. The cross-sections of the bonding interfaces are mechanically polished to reveal the microstructure of the intermetallic compounds at the bonding interfaces. The microstructures are then characterized by scanning electron microscopy (SEM). Energy dispersive X-ray spectroscopy (EDX) is used to determine the phase composition of the IMC layers. In order to evaluate the mechanical reliability of the SLID joints, shear tests are conducted on Nordson DAGE 4000 bond tester with shear speed at 300 $\mu\text{m/s}$.

3. Results and Discussion

Fig. 2(a) illustrates the cross-sectional of the metallization of the Si chips sample and the bonding structure. Fig. 2(b) presents the cross-sectional analysis of the bonded Si/Cr/Cu/Ni/Sn sample acquired with SEM. Based on the EDX analysis, the sample has the composition of Ni_3Sn_4 at the Ni-Sn bonding interface, where both sides are sandwiched by a layer of Ni. The Sn layer has transformed to the IMC phase Ni_3Sn_4 and continues to grow in a scallop-like form during the bonding process. It can be seen that the scallop-like growth of Ni_3Sn_4 has induced the formation of voids at the bonding interface. These voids start to grow and eventually become continuous cracks. In principle, these cracks will also reduce the path for interdiffusion between Ni and Sn atoms, resulting in poor bonding and reliability issues in wafer-level interconnections.

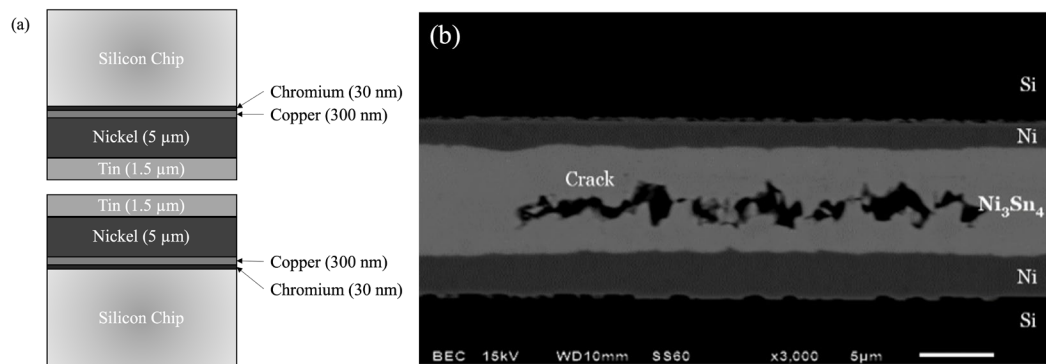


Fig. 2 (a) Schematic diagram and (b) SEM image of cross-section of SLID bonded Si/Cr/Cu/Ni/Sn at 250 °C for 30 min.

Fig. 3(b) shows the cross-sectional microstructures of the joints formed by the SLID bonding of Si/Cr/Cu/Ni with Si/Cr/Cu/Ni/Sn/Ag. Interestingly, by adding a layer of Ag, full intermetallic joint Ag_3Sn and Ni_3Sn_4 is obtained after the bonding process, where the bonding interface is presented as much better integrity than the Ni-Sn bonded joint in Fig. 2(b). More importantly, the connection layer is visibly continuous along the cross-section. Similar to the Ni-Sn bonded sample in Fig. 2, a thin layer of scallop-like Ni_3Sn_4 formed at the interface of the Si/Cr/Cu/Ni/Sn/Ag side, and a layer of Ag-Sn IMC is observed in between the scallop-like Ni_3Sn_4 and Ni layer, forming Ag_3Sn . The initial Sn and Ag layer has been consumed completely by the IMC formation. The large cracks found in the Ni-Sn joint now become numerous small voids distributed in the Ag layer. Obviously, the interdiffusion of Ag and Sn atoms forms Ag_3Sn and fills up the voids formed by the formation of scallop Ni_3Sn_4 IMC. Although the voids probably existed in the Ag_3Sn and Ni_3Sn_4 IMCs layer, the sample can still be successfully bonded. Here, only the Ni bottom layer is consumed for the IMC formation as Sn is directly diffused into Ni and Ag to yield Ni_3Sn_4 and Ag_3Sn respectively. Yet, the growth of Ni_3Sn_4 is suppressed by the insolubility of Ag in Ni_3Sn_4 and the formation of Ag_3Sn at the Ni/Sn interface [27]. During the bonding process, the molten Sn tends to diffuse through the grain boundaries of Ni_3Sn_4 to reach Ag. As Ag_3Sn is formed along with the growth of the bottom Ni_3Sn_4 layer. As most of the Sn is consumed by the formation of Ag-Sn IMC, the leftover Sn available will be insufficient to promote the Ni_3Sn_4 growth, which results in a much thinner Ni_3Sn_4 layer formed. This phenomenon has been previously reported in conventional Sn solder joints [22, 23] and was confirmed in literature [24-26].

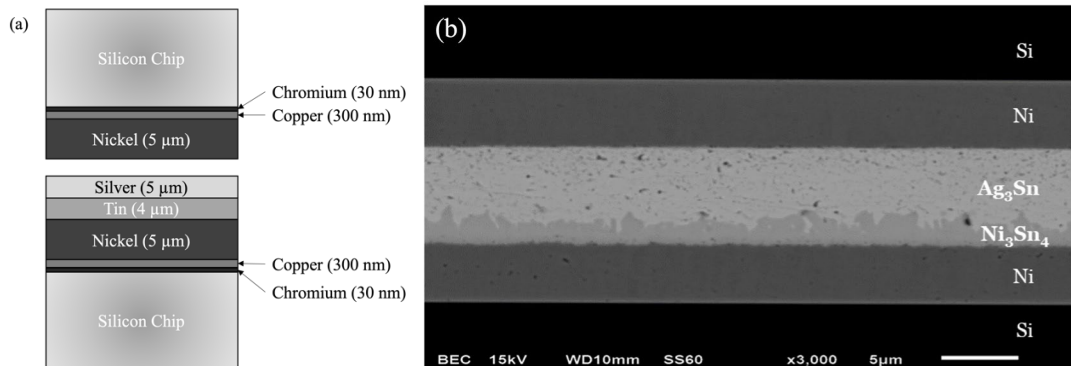


Fig.3 (a) Schematic diagram and (b) SEM image of cross-section of the formation of void-free interface for the solid liquid interdiffusion bonding of Si/Cr/Cu/Ni with Si/Cr/Cu/Ni/Sn/Ag at 250°C for 30 min.

In order to further investigate the effect of Ag₃Sn IMC filling on the crack formation, the Ag/Sn SLID bonding is conducted by Si/Cr/Cu/Ni/Sn with Si/Cr/Cu/Ni/Sn/Ag to perform a Ni/Sn/Ag/Sn/Ni interfacial reaction. In this case, the IMC formation of Ni₃Sn₄ is expected to form at both the upper and lower interfaces. Moreover, a great amount of molten Sn during bonding can generate continuous growth of the scallop-like Ni₃Sn₄ and eventually impinge on each other at the bonding interface to form a relatively thicker IMC layer in comparison to the SLID bond formed with Si/Cr/Cu/Ni/Sn/Ag and Si/Cr/Cu/Sn. The rapid formation of Ni₃Sn₄ IMCs will lead to the formation of large voids at the bonding interface upon subsequent cooling process. Surprisingly, these voids caused by the Ni₃Sn₄ IMCs are filled with Ag₃Sn to form a perfect bonding interface, as shown in Fig. 4(b).

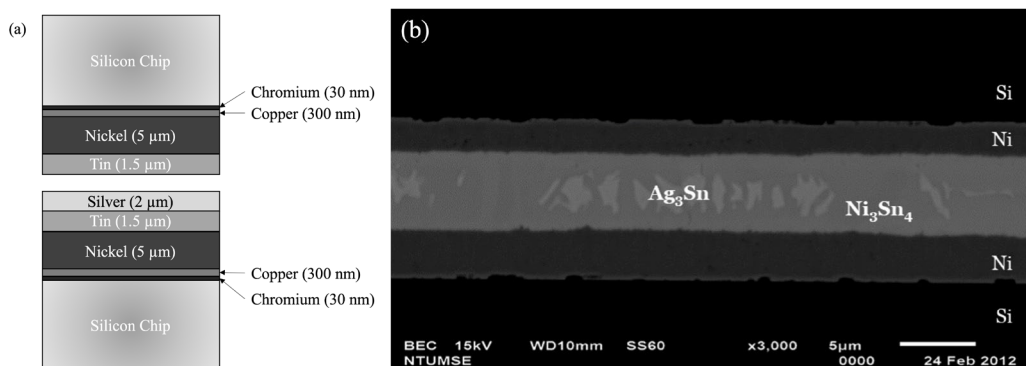


Fig.4 (a) Schematic diagram and (b) SEM image of cross-section of the formation of void-free interface for the solid liquid interdiffusion bonding of Si/Cr/Cu/Ni/Sn/Ag and Si/Cr/Cu/Sn at 250°C for 30 min.

Shear tests are conducted to investigate the correlation between the microstructural evolution and the mechanical reliability of the SLID joints. The measured shear strengths of the three SLID joints are plotted in Fig. 5. The SLID bonding of two Si/Cr/Cu/Ni/Sn chips exhibits severe cracks within the structure, and exhibits a shear strength of about 13 MPa. However, adding a 5 μm-thick Ag layer does not improve much in terms of shear strength about 15 MPa in the SLID bonding of Si/Cr/Cu/Ni with Si/Cr/Cu/Ni/Sn/Ag. This is attributed to the overgrowth of Ag₃Sn at the bottom metallization and the formation of micro-voids within the Ag₃Sn layer. However, with a 2 μm-thick Ag layer sandwiched by two Ni layers, the shear strength increases drastically to 20 MPa due to the void free interconnection formed.

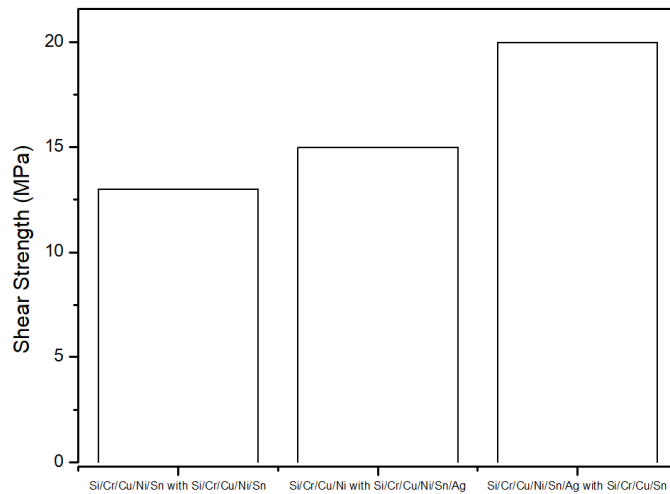


Fig. 5 Shear strengths of various SLID Ni/Ni joints for Si/Si wafer bonding.

According to previous literature, SLID bonding on the Ag-Sn binary system has been well-established for power devices operating at high temperatures. Especially the Ag_3Sn IMCs possess excellent thermal and electrical conductivities as well as higher mechanical properties (i.e. ductility) than other IMC phases like Cu_6Sn_5 and Ni_3Sn . These mentioned properties are highly desirable in electronics applications, which provides Ag_3Sn a great potential to offer consistently high performance and reliable interconnections in harsh environments. However, only a few reports have been found to report the Ag filling behavior at the cracks formed by the scalloped Ni_3Sn_4 growth. To assess the Ag_3Sn filling kinetics of SLID bonded samples, a series of microstructural evolutions at the bonding interfaces are carefully compared based on the variation in the joint morphologies of the bonded samples. For the Ni-Sn SLID bonding, Sn is usually in molten state due to the low melting point and readily diffuse to adjacent Ni metallization to form IMCs. As a result, Ni_3Sn_4 grains with scallop-like morphology formed at both the upper and lower interfaces (Fig. 6(b)), where the molten Sn layer remains in the joint. Prolonged bonding time allows more interdiffusion of the Ni and Sn atoms, leading to the scalloped Ni_3Sn_4 growth (Fig. 6(c)). Due to brittle nature of Ni_3Sn_4 grains, the impingement of the top and bottom Ni_3Sn_4 layers takes place with no plastic deformation. As the molten Sn is completely consumed by the thickening of Ni_3Sn_4 layers, these vacancies are concentrated at the boundaries of Ni_3Sn_4 phases, and these areas are connected to each other to form large continuous cracks at the bonding interface (Fig. 6(d)).

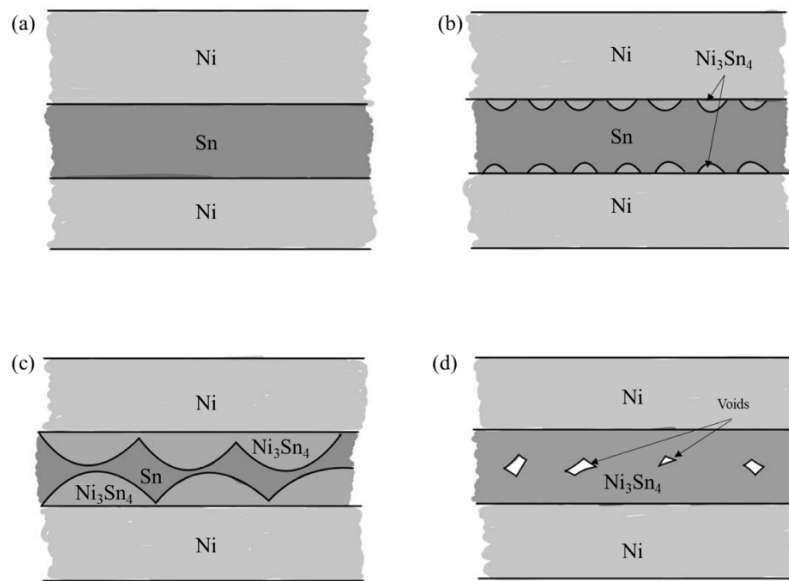


Fig. 6 Large voids formed at the interface of SLID- joint for two Si/Cr/Cu/Ni/Sn after bonding at 250 °C for 30 min.

However, it was suggested that the presence of voids and cracks at the bonding interface during bonding is significantly affected by the reaction of the Ag and Sn layer. In contrast to the SLID joint of Ni/Sn/Ni structure, a continuous Ag_3Sn intermetallic layer is formed accompanied with the scallop-like Ni_3Sn_4 intermetallic phase as shown in Fig. 7.

Furthermore, the Ag_3Sn , a ductile intermetallic compound formed in between the Ag-Sn interface [25], presented as isolated islands in between the impinging Ni_3Sn_4 layer (Fig. 8(b)). During the bonding process, Ag_3Sn starts to migrate along the joint and flattened in between the top and bottom Ni_3Sn_4 layers (Fig. 8(c)). Although the growth of Ni_3Sn_4 proceeds until all Sn has been completely exhausted, leaving a large number of vacancies in the Ni/Sn interface, the impinging Ni_3Sn_4 layers squeezes the Ag_3Sn forward, and eventually trapped in the voids and flattened in between the Ni_3Sn_4 at the bonding interface (Fig. 8(d)). From the overall microstructural evolutions of the bonded samples with an Ag layer, we found that the growth of Ag_3Sn has successfully suppressed the crack formation at the bonding interface, which is favorable for the electrical performance of the chip stack, as well as enhancement in the mechanical properties of the SLID joints. The elimination of voids by Ag_3Sn filling shows significance to the bond integrity as well as ensures the long-term reliability of the SLID joints.

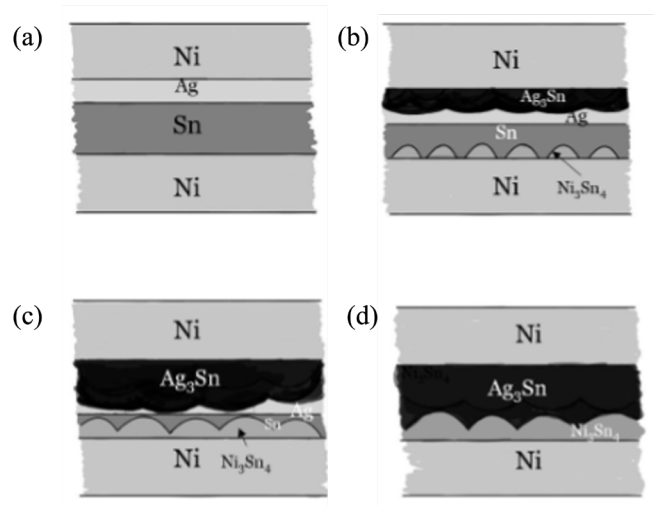


Fig. 7 Formation of void-free interface for the solid liquid interdiffusion bonding of Si/Cr/Cu/Ni/Sn/Ag with Si/Cr/Cu/Sn.

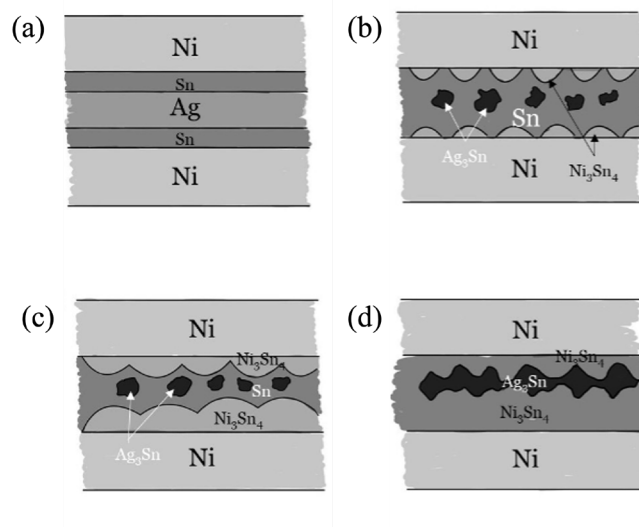


Fig. 8 Formation of void-free interface for the solid liquid interdiffusion bonding of Si/Cr/Cu/Ni/Sn/Ag with Si/Cr/Cu/Sn.

Die attachments of power modules applying SLID methods are also conducted. Fig. 9(a) represents the structure of die bonding of metallized Si chips and DBC substrates, containing the metallization of Ti/Ni/Sn on Si chips and bonded with Ni/Pd/Au coated on DBC substrates. Fig. 9(b)(c)(d)(e) are the morphologies of the bonding interface after bonding for 30 minutes at 275 °C, 300 °C, 350 °C, and 400 °C, respectively. The increase of bonding temperature at fixed bonding time is aimed to reduce the voids and gaps, as higher temperature provided kinetic energy for the atomic movement. In Fig. 9(b), the voids appear at the bonding interface. When increase the bonding temperature to 300 °C, 350 °C, and 400 °C, as shown in Fig. 9(c)-9(e), Ni₃Sn₄ intermetallic compounds were generated at the bonding interface due to the diffusion of Sn into Ni layer. However, huge gaps and voids that could deteriorate the bonding strength and joint reliability were also detected. When the bonding temperature was rise to 400 °C, the intermediate layer tended to become thinner due to the solid solution effect.

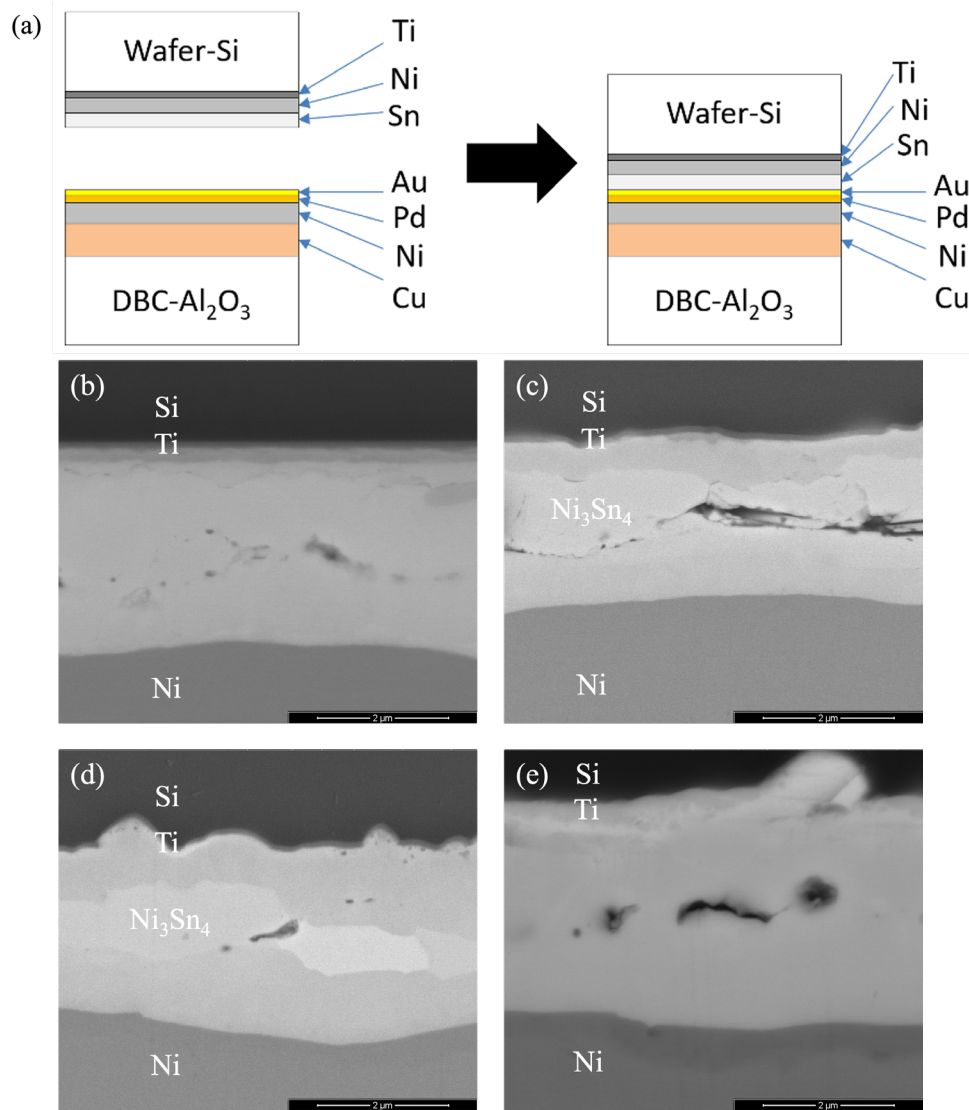


Fig. 9 (a)The structure of the SLID bonding samples and the morphologies of the bonding interfaces of Si/Ti/Ni/Sn diffusion bonded with DBC Cu/Ni/Pd/Au for 30 min at (b) 275 °C, (c) 300 °C, (d) 350 °C, (e) 400 °C.

Fig. 10 depicted the measured average bonding strength and the under different bonding temperature. The lowest average bonding strength was measured to be 6.15 MPa when bonded with the lowest temperature of 250 °C. The bonding strength increased slightly as higher bonding temperature were applied. When the bonding temperature was raised to 350 °C, highest average bonding strength of 18.03 MPa was acquired. However, the holes and gaps at the bonding interface cannot be effectively eliminated with higher temperature, which will jeopardize the bonding joint.

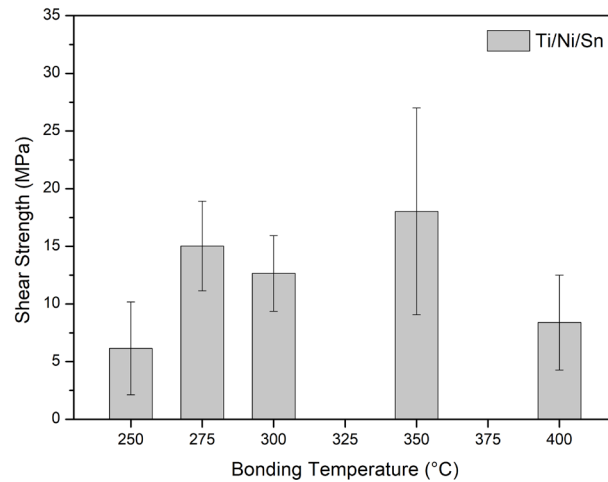
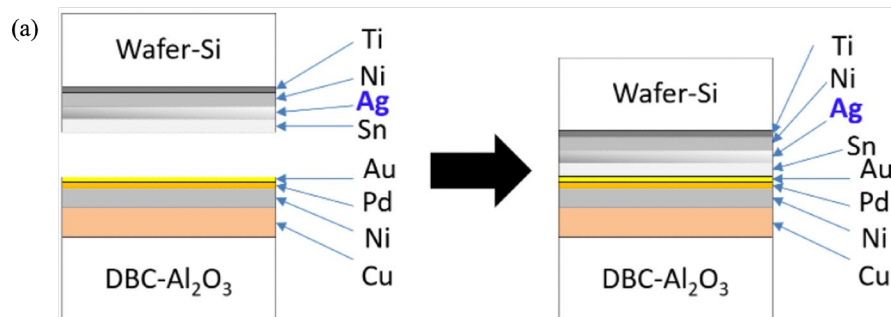


Fig. 10 Average bonding strengths of the wafer Si/Ti/Ni/Sn and DBC Cu/Ni/Pd/Au bonded for 30 min at various bonding temperatures.

To improve the bonding strength and reliability, Ti/Ni/Ag/Sn backside metallization structure were applied to for the SLID bonding process, as shown in Fig. 11(a). The cross-sectional morphologies of different bonding temperature for bonding time of 30 minutes are also inspected in Fig. 11(b)-(e). With the bonding temperature of 275 °C, an average thickness of 0.5 μm of Ag₃Sn were located between IMCs of Ni₃Sn₂ and Ni₃Sn₄. Some of the Sn diffused upward and react with the Ni deposited on the Si chips, forming Ni₃Sn₂, other diffused downward to react with the Ni deposited on the DBC substrates and formed Ni₃Sn₄. No voids or gaps were found at the bonding interface. Fig. 11(c) is the cross-sectional SEM image when bonding at 300 °C, Ag₃Sn were formed between the two Ni₃Sn₄ sections. Increased the temperature to 350 °C and 400 °C, as shown in Fig. 11(d) and (e), a uniform intermediate layer composed of Ag₃Sn were formed at the bonding interface.



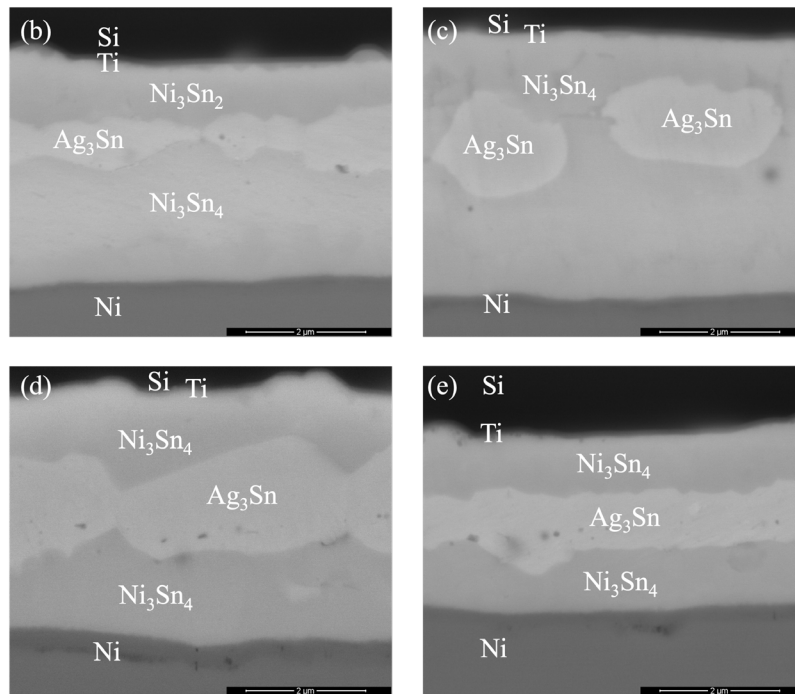


Fig. 11 (a)The structure of the SLID bonding samples and the morphologies of the bonding interfaces of Si/Ti/Ni/Ag/Sn diffusion bonded with DBC Cu/Ni/Pd/Au for 30 min at (b) 275 °C, (c) 300 °C, (d) 350 °C, (e) 400 °C.

Measuring the bonding strength of four different bonding temperature SLID samples with Ti/Ni/Ag/Sn backside metallization structure bonded with DBC substrates, the results were depicted in Fig. 12. The average bonding strength were ranged from 13.12 MPa to 19.75 MPa. When the bonding temperature were set to be 275°C, the average bonding strength was 19.75 MPa, which was slightly higher than that of the Ti/Ni/Sn bonded with DBC substrates. Ag_3Sn possess similar mechanical properties with pure silver, which makes it perfect candidates to act as a stress buffer layer. The ductile Ag_3Sn intermetallic compounds filled the voids between the brittle Ni_3Sn_4 IMCs, which attributes to the forming of almost a void-free interface and the therefore increase the bonding strength in a lower temperature. At higher temperature of 300 °C, 350 °C, and 400 °C, the bonding strength slightly decreased, but remains higher than the structure without the addition of Ag layer.

Comparing the cross-sectional morphologies and average bonding strength of two bonding structure of Ti/Ni/Sn and Ti/Ni/Ag/Sn. The results showed that with the additional layer of silver, the die attachment methods of SLID can be optimized. The IMCs that formed after thermal pressure bonding can withstand higher temperature than the operation temperature of the power modules. High-temperature applications and reliable interconnections can be achieved in harsh environments. Therefore, this SLID possess great potential in field of the power module electronic packaging.

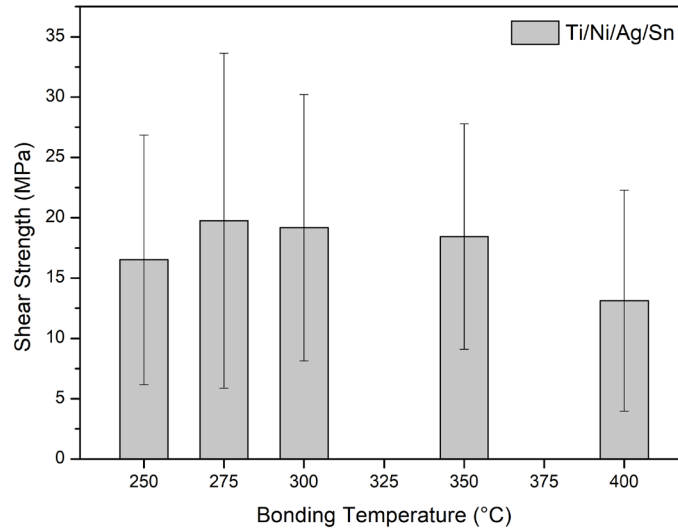


Fig. 12 Average bonding strengths of the Si/Ti/Ni/Ag/Sn wafer and DBC Cu/Ni/Pd/Au bonded for 30 min at various bonding temperatures.

4. Conclusion

In this study, the interfacial reaction and the microstructural evolution of the SLID bonding Ni-Sn system were investigated by comparing the cross-sectional morphologies and the average bonding strength of Cr/Cu/Ni/Sn with Cr/Cu/Ni/Sn/Ag structure. In addition, a mechanism of Sn-Ni-Ag SLID bonding system was proposed. The scallop-like Ni_3Sn_4 intermetallic compounds formed between the Ni and Sn layers. During the process of SLID bonding, the impingement due to the brittle nature of IMCs caused huge voids and gaps at the bonding interface and decrease the bonding strength. With the addition of Ag layer between the Ni and Sn layers, ductile Ag_3Sn intermetallic compounds formed between the brittle Ni_3Sn_4 . Die attachment of DBC/Ni/Pd/Au with Ti/Ni/Sn and Ti/Ni/Ag/Sn were also conducted. The results showed diminished voids and gaps after addition of Ag layer to form the IMCs of Ag_3Sn . A void-free interface and the improvement of average bonding strength up to 19.15 MPa can be attributed to the filling of voids at the interface by Ag_3Sn IMCs. The results showed great potential of the application of Ag_3Sn intermetallic interlayer in SLID bonding process in the field of power modules.

Acknowledgements

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