# Effect of Ni$_3$Sn$_4$ on the Thermo-Mechanical Fatigue Life of Solder Joints in 3D IC

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In this article, the 3D integration with Ni/Sn/Ni joints was conducted using transient liquid phase (TLP) bonding (250°C, 0.2 N) with different bonding time. After TLP bonding, plane-type Ni$_3$Sn$_4$ intermetallic compound (IMC) was observed, and when the bonding time is 180 min, complete Ni$_3$Sn$_4$ was found. The diffusion coefficient $D$ was determined to be 32.4 $\mu$m$^2$/min. Based on the finite element (FE) simulation, the results demonstrated that the shear stress and equivalent creep strain increased obviously with an increase in the IMC thickness; the results calculated show that the IMC thickness impacts the fatigue life of solder joints significantly, and the fatigue life decreases notably with an increase in the Ni$_3$Sn$_4$ thickness.

**Keywords: 3D IC, TLP bonding, IMC thickness, fatigue life, solder joints**

## INTRODUCTION

With the development of chip technology, three-dimensional (3D) integrated circuits (IC) technology overcomes the limits of Moore's law to ensure the chip (or wafer) vertical stacking (Zhang et al., 2018; Zhang and Liu, 2020); due to the advantages of relatively low temperature bonding and high temperature service, transient liquid phase (TLP) bonding has gradually become an attractive bonding technology in 3D chips stacking with complete intermetallic compound (IMC). The formation and growth of IMCs of solder joints play an important role in the electronic devices (Xiong and Zhang, 2019). In order to obtain IMC solder joints, Cu/Sn, Cu/In, and Ni/Sn, i.e., have all been considered in 3D chips stacking with TLP bonding. For Cu/Sn TLP bonding (Chen and Duh, 2017), studied the microstructures evolution of Cu/Sn-3.5Ag/Cu-xZn using TLP bonding; it can be found that the addition of 15% Zn into Cu substrate can availably maintain the IMCs multi-orientation structure and restrain the growth of Cu$_3$Sn layer during aging. For Cu/In bonding, Cu$_{11}$In$_9$ and Cu$_2$In, two IMCs, layers can be observed simultaneously during isothermal storage (Panchenko et al., 2018). In this article, we have studied the formation of Ni$_3$Sn$_4$ IMC with different bonding time using TLP bonding; moreover, the finite element code was utilized to calculate the stress–strain distribution to predict the effect of IMC thickness on the fatigue life of solder joints.

## EXPERIMENTAL AND FEM ANALYSIS

Sn paste was applied on the surface of Ni substrate to form Ni/Sn/Ni joints to simulate 3D integration, which was performed using TLP bonding (250°C, 0.2 N) with different bonding time. The Ni/Sn/Ni specimens were prepared with resin inlay and polished after bonding, and etched
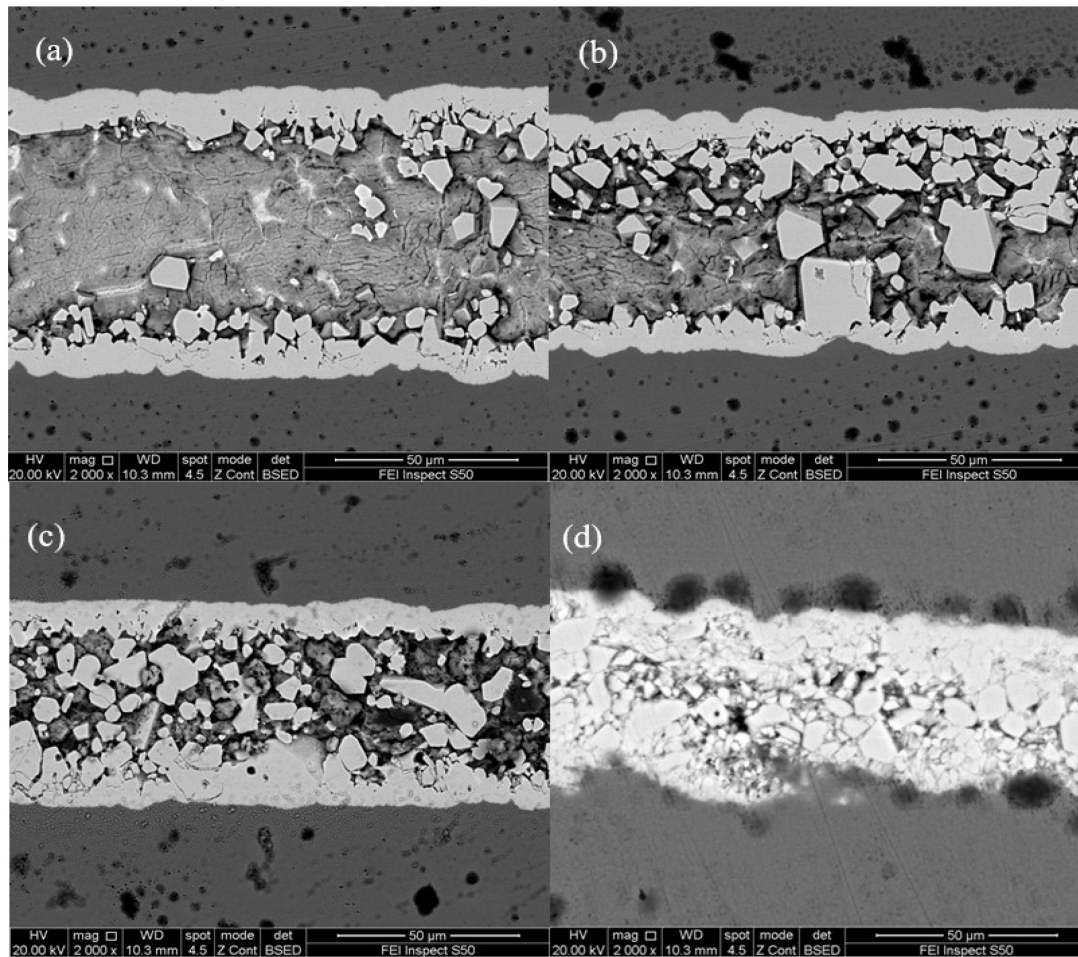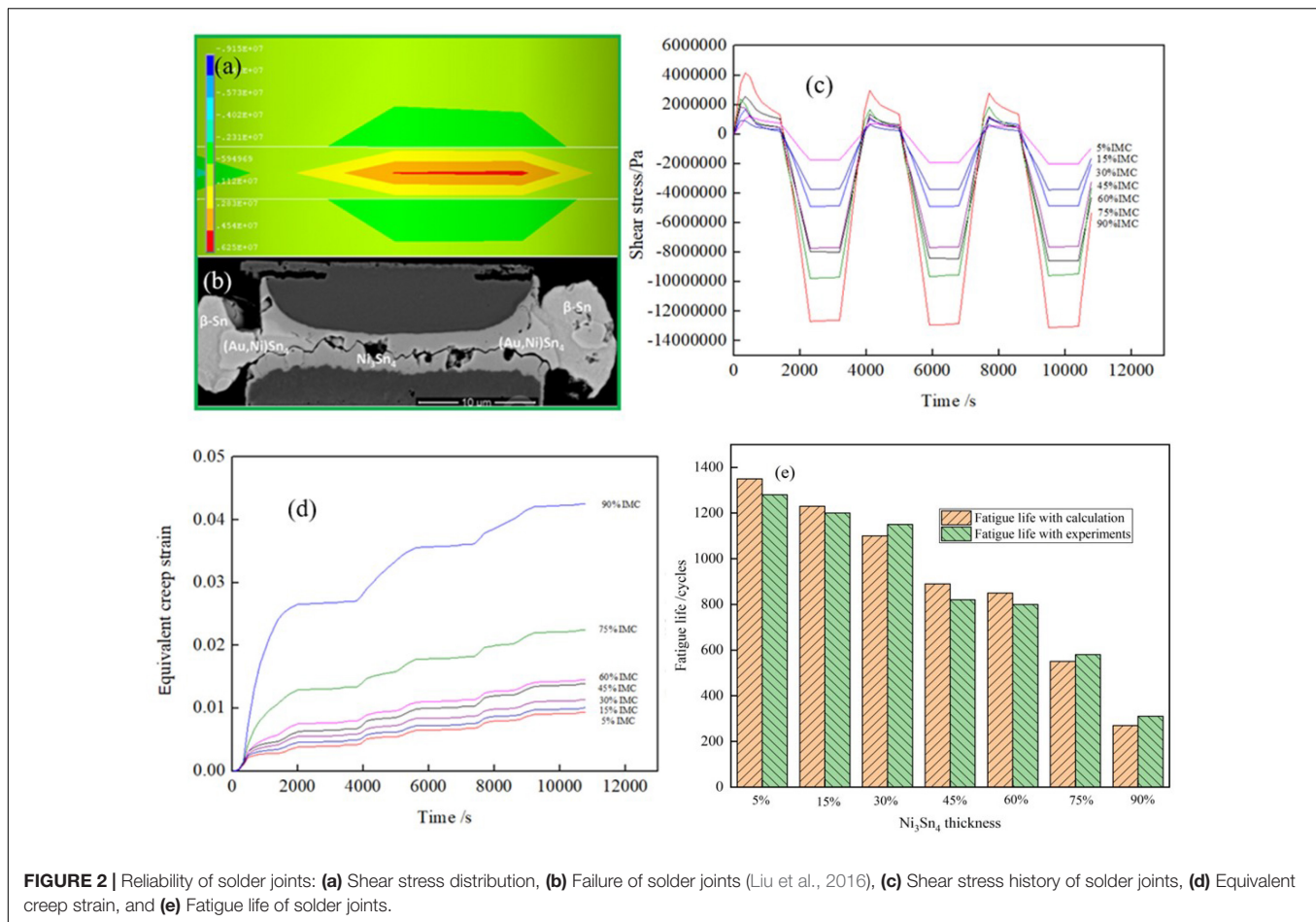
**FIGURE 1 |** Solder joints with different bonding time: **(a)** 10 min, **(b)** 15 min, **(c)** 40 min, and **(d)** 180 min.

with a mixture of 95% methanol and 5% nitric acid for 20 s; the microstructures of Ni/Sn/Ni joints were observed by scanning electron microscopy (SEM). Meanwhile, due to the geometric symmetry of the 3D IC, a quarter finite element model of the 3D structure was established to simulate the stress–strain distribution of IMC solder joints with different thicknesses. In the model SOLID186, a 20-node hexahedral element was selected to simulate the 3D structure, and a sweep mesh method was utilized in modeling. Thermal cyclic loading (218 K to 398 K) was loaded onto the 3D structure to assess the reliability of Ni/Sn/Ni joints.

## RESULTS AND DISCUSSION

Due to the high Sn in the solder joints, the $Ni_3Sn_4$ phase can be formed at the Sn/Ni interface after TLP bonding with different bonding time according to the Ni-Sn phase diagram. After 10 min bonding, the nucleation of $Ni_3Sn_4$ phase was observed for the formation of $Ni_3Sn_4$ IMC layer. The average thickness of $Ni_3Sn_4$ at the interfacial layer is approximately 18 µm. **Figure 1a** shows the microstructure of Ni/Sn/Ni joint.

In an electronic device, during soldering, the molten Sn-based solder was spread on Cu substrate to form Cu-Sn IMC; the scallop-type $Cu_6Sn_5$ phases were detected at the interfacial microstructure, and for Ni/Sn/Ni structure, the plane-type $Ni_3Sn_4$ IMC was demonstrated. With the variation of bonding time from 10 to 180 min as shown in **Figure 1**, the IMC thickness of $Ni_3Sn_4$ increases markedly (**Figures 1b,c**). When the bonding time is 180 min, complete $Ni_3Sn_4$ was found as shown in **Figure 1d**. Ghosh (2000) proposed that at a certain temperature during soldering, the Sn content can determine the thickness of the remainder Cu/Ni/Pd metallization during Ni-Sn reaction; higher Sn content can induce a faster reaction rate, so pure Sn was selected as the interconnect material for 3D chip stacking. Higher Sn content can improve the formation of completed IMC joints. In the investigation of IMC growth, the IMC growth rate is directly proportional to the square root of heating time, with the consideration of IMC growth controlled by volume diffusion (Zhang and Gao, 2015). Equation $\left(X_t = \sqrt{Dt}\right)$ represents the relationship between IMC thickness and the time; the diffusion coefficient $D$ was determined to be 32.4 $\mu m^2$/min, which demonstrates that the diffusion coefficient

**FIGURE 2** | Reliability of solder joints: **(a)** Shear stress distribution, **(b)** Failure of solder joints (Liu et al., 2016), **(c)** Shear stress history of solder joints, **(d)** Equivalent creep strain, and **(e)** Fatigue life of solder joints.

is higher obviously under liquid-state reaction than that under solid-state reaction.

In order to further study the $Ni_3Sn_4$ joints in 3D structure, finite element code was selected to calculate the stress–strain distribution. Three-dimensional finite element model can be established with a SOLID186 element; the solder joint has a diameter of 150 µm and a height of 70 µm; the size of the Cu substrate is 150 µm × 150 µm. For the finite element simulation, Garofalo-Arrhenius creep model (Xiong Ming et al., 2020) can be utilized to describe the creep and stress–strain of the solder joints during thermal cycle loading; the properties of Cu substrate do not change much with the temperature, so it is assumed that the material is a linear elastic material, as shown in our previous work (Xiong Ming et al., 2020; Zhang et al., 2020b). In addition, for the post-processing, the maximum stress–strain in the critical node of solder joints was used to evaluate the stress–strain response. **Figure 2a** shows the shear stress in the $Ni_3Sn_4$ solder joints; the results indicate the shear stress distribution in the three-dimensional 3D structure with different colors, and the maximum shear stress with red color was observed in the middle of $Ni_3Sn_4$ IMC. In lead-free soldering, the Cu-Sn IMCs were the stress concentration locations (Ghosh et al., 2017; Li et al., 2018; Zhang et al., 2020a). Therefore, this area along the $Ni_3Sn_4$ IMC layer was demonstrated to be the critical location, which may be

the failure zone in service. The CTE mismatch among $Ni_3Sn_4$, Ni, and chip can induce the phenomenon. Moreover, the $Ni_3Sn_4$ is a brittle phase, and combining the stress concentration, the cracks can be produced and propagated in the $Ni_3Sn_4$ IMC. **Figure 2b** displays the cracks along the $Ni_3Sn_4$ IMC in the experiment (Liu et al., 2016). **Figures 2a,b** confirm that the stress concentration area is the area where cracks appear, and the experimental results agree well with the finite element simulation results. **Figure 2c** plots the shear stress history of the stress concentration location in the solder joints with different IMC thickness; it was found that with the increase in IMC thickness, the shear stress increased obviously under three thermal cyclic loading, and the shear stress induced the IMCs to break away from the interface in service (Teo and Sun, 2008). **Figure 2d** plots the equivalent creep strain time history of IMCs joints with different IMC thickness. It was demonstrated that an increase in the IMC thickness can dramatically cause an increase of equivalent creep strain; the IMC joints are the key part of the 3D assembly, and the largest creep strain was observed in the IMC joints. Moreover, the fatigue life of solder joints was predicted with the fatigue life prediction model $\left(N_f = (0.0405\varepsilon_{acc})^{-1}\right)$ based on the largest equivalent creep strain. The fatigue life of solder joints with different IMC thickness was calculated as shown in **Figure 2e**. It was observed that the IMC thickness can impact the fatigue life of solder joints

significantly. An increase in the $Ni_3Sn_4$ thickness induced an increase in the fatigue life markedly, and a similar phenomenon was found in both Sn3.9Ag0.6Cu solder joints (Choudhury and Ladani, 2015) and Sn3.8Ag0.7Cu solder joints in 3D packaging (Zhang et al., 2017). From **Figure 2e**, the solder joints with 90% IMC thickness reduced the fatigue life predicted to about 23% compared to the case with 5% IMC thickness. Moreover, the experimental results agreed well with the calculation results. Therefore, in 3D chip stacking, an increase in the IMC thickness to carry out high-temperature service may decrease the fatigue life, and how to enhance the fatigue life of IMC joints may be an important topic in 3D chip stacking.

## CONCLUSION

The formation of $Ni_3Sn_4$ IMC with different bonding time using TLP bonding was studied. An increase in the bonding time can cause an increase in the $Ni_3Sn_4$ thickness dramatically. When the bonding time is 180 min, complete $Ni_3Sn_4$ was formed. Moreover, the maximum shear stress was observed in the middle of $Ni_3Sn_4$ IMC joints in the 3D structure; with the increase in the $Ni_3Sn_4$ thickness, the fatigue life of solder joints was reduced markedly.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

LZ analyzed and interpreted the patient data and was a major contributor in writing the manuscript. S-JZ was responsible for revising the grammar of the manuscript. Both authors read and approved the final manuscript.

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