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Utilizing Co as a contact metallization for wafer-level Cu-Sn-In SLID bonding used in MEMS and MOEMS packaging

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***Abstract*—Many MEMS and MOEMS devices require hermetic packaging with preferably no postprocessing after the MEMS device's releasing. Wafer-level Solid-Liquid Interdiffusion (SLID) bonding can provide simultaneous hermetic packaging and better electrical interconnects. Moreover, employing a physically deposited contact metallization on the device wafer instead of chemically deposited layers (such as electrochemical Cu) is of utmost importance as far as reducing the complexity of the MEMS/MOEMS packaging process integration is concerned. The current work studied the possibility of utilizing Co as a contact metallization layer for the low-temperature Cu-Sn-In-based SLID bonding. In order to guarantee the long-term reliability of the devices, a fundamental understanding of the formation and evolution of interconnection microstructures and mechanical characterization of the joint is of utmost importance. In this work, Cu-Sn-In electroplated Si chips were bonded to Co substrates at a temperature range 160-250°C. During the bonding process, a single intermetallic compound (IMC) $(Cu,Co)_6(Sn,In)_5$ formed at the bonding area, with no detectable Cu3Sn phase that causes voids formation. The Young's modulus and hardness of $(Cu,Co)_6(Sn,In)_5$ and Cu_6Sn_5, as a reference, were measured as 124.8±0.5 and 6.2±0.5, 114±1 and 6.7±0.5 MPa, respectively. Furthermore, the current study was able to produce a fully IMC joint of Cu-Sn-In/Co SLID system at 220°C for bonding time as short as 20 minutes.**

Keywords— Cu-Sn SLID bonding, Cu-Sn-In SLID bonding, TLP bonding, Co contact metallization, Reliability.

I. INTRODUCTION

Solid-liquid interdiffusion (SLID) bonding, also known as transient liquid phase (TLP) bonding, is a promising process for wafer-level packaging of MEMS/MOEMS devices providing both hermetic sealing and electrical interconnections [1]–[3]. The process is performed in a sandwiched structure of at least a low-melting temperature (LT) metal between two high-melting temperature (HT) metals or metallization stacks. Utilizing the low-melting temperature metals in SLID bonding method bene-fits the wafer-level packaging of MEMS/MOEMS devices by reducing the bonding temperature [1], [4]. The SLID layers' thicknesses are designed such that the low-temperature metal is totally consumed, and the bond is entirely composed of IMCs with high-melting temperatures. Hence, joints show better thermal stability than the traditional eutectic and solder bonding methods. Utilizing different metal stacks can benefit various devices and manufacturability requirements. Several different binary SLID systems (such as Au-Sn, Au-In, Cu-Sn, Cu-In, Ag-Sn, and Ni-Sn) have been previously studied [1]–[3], [5]–[8]. Cu-Sn SLID system is one of the most popular material systems utilized in MEMS encapsulation and interconnection due to its low process temperature (250–350 °C), high thermal stability, and excellent mechanical reliability [9]. For many applications, it is of great interest to further reduce the bonding temperature, and thereby to minimize bonding induced re-sidual stresses. Hence, In has been known as a potential candidate to replace Sn as it has a melting temperature of 80°C below the Sn melting point.

Several studies have been conducted to investigate the low-temperature Cu-In bonding [2], [10]–[15]. At room temperature, the stable phases in Cu-In binary system are Cu, , and In. Based on the previous experimental results and the Cu-In binary phase diagram, various IMCs (Cu_7In_3 (δ), Cu_2In (η), $Cu_{11}In_9$, $CuIn_2$, $Cu_{16}In_9$, and CuIn) can appear during bonding [2], [3], [10]–[13], [16], [17], and phase transformation can occur during aging. Voids with different sizes appear after aging due to the volume shrinkage between different phases [15]. According to Roy[18] and Chen[19], the CuIn intermetallic compound forms even at room temperature, and it can be formed immediately after In deposition on Cu. The early formation of IMCs like CuIn hinders the Cu dissolution into In, and the IMCs formation takes place slower. Hence, the plausible drawbacks of the Cu-In SLID system are poor mechanical properties due to the void formations during aging and limited storage time due to IMCs formation before bonding.

Combining two binary systems to a ternary or higher order SLID systems can benefit wafer-level packaging of MEMS/MOEMS devices such as lower bonding temperature, and better physical properties for higher functional performance and long-term reliability [1]. The ternary Cu-Sn-In system establishes a promising low-temperature bonding system as the eutectic temperature of Sn-In is almost 40° below the melting point of In [1], [13]. Utilizing low-melting temperature Sn-In (either alloy or layered structure) for SLID systems instead of using pure Sn or In offers several advantages: 1) a higher solubility of the HT metal (Cu) into the LT liquid phase (which is a critical parameter in reaction kinetics), 2) lower bonding temperature, 3) higher re-melting temperature, 4) decreasing the complexity of the IMCs form in the bond area compared to Cu-In, and 5) stabilizing Cu_6Sn_5 and hindering the Cu_3Sn phase formation (which is followed by void formation) [1]. Various studies have investigated the microstructural evolution and bond reliability of the Cu-Sn-In system. D-Q Yu[13] et al. obtained a reliable bond (analyzed by hermeticity and shear tests) via Cu-Sn-In wafer-level bonding at 180°C. According to V. Vuo-rinen[2], Cu-Sn-In SLID bonding, even at a low bonding temperature of 170 °C for one hour, can show high strength bonds with low defect content. They reported that the bonding temperature impacts the reaction products and the number of de-fects: 1) Cu_3Sn phase and $Cu_6(Sn,In)_5$ with several voids at Cu_3Sn/Cu interface at a bonding temperature of 250°C, and 2) void-free single $Cu_6(Sn,In)_5$ at 150°C and 170°C. O. Golim et al.[20] bonded Si wafer to different optically transparent mate-rials at 200°C. The bond was composed of the single $Cu_6(Sn,In)_5$ phase.

Considering the abovementioned discussion, the Cu-Sn-In SLID system is a promising candidate for MEMS/MOEMS packag-ing. However, there are still typical challenges in process integration of interconnection methods requiring wet-chemistry, such as electroplating of the Cu metal on the device wafers containing sensitive MEMS/MOEMS devices. In addition, accord-ing to previous research, the Cu-Sn-In system shows two different reaction products ($Cu_6(Sn,In)_5$ and Cu_3Sn) [2]. Cu_3Sn for-mation is mostly followed by voids formation, which deteriorates the bond quality. Hence, the current study aimed to utilize a physically deposited contact metallization on the device wafer, which can also inhibit the Cu_3Sn formation. Our previous work showed that Co is a promising contact metallization for the Cu-Sn system as it can be sputtered on device wafers. Fur-thermore, Co can stabilize the Cu_6Sn_5 phase and inhibit the Cu_3Sn phase formation. However, before introducing a new met-al for contact metallization in Cu–Sn-In SLID bonding, a comprehensive understanding of the interfacial reactions is of ut-most importance. Therefore, we studied the microstructural evolution of the bulk Co in contact with Cu-Sn-In electroplated Si chip at a temperature range of 170-250°C. In addition, we measured the mechanical properties of the bond area using a nanoindentation test..

II. MATERIALS AND METHODS

A. Specimen preparation

All samples were prepared on thermally oxidized (300 nm SiO2) 4” Si〈100〉 wafers. A 60nm thick TiW adhesion layer was sputtered on cap wafers, and it was followed by a 100 nm thick copper seed layer sputtering. 4 μ m of copper was electroplated utilizing NB Semi plate Cu 100 bath, followed by 2μm of the electroplated tin using NB Semi plate Sn 100 solution from NB technologies, and 2μm of the electroplated indium using indium sulfamate plating bath. Cu–Sn-In metallized wafers were cut into 1 × 1 cm2 pieces. Co foil (purity: 99.99%, Goodfellow Ltd.) 1 mm in thickness was cut into pieces 1 × 1 cm2 in size. The pieces were mechanically ground to 2400 papers, cleaned with acetone, and air-dried before bonding. Finally, the prepared Cu-Sn-In electroplated chips in contact with Co foil pieces were placed in a metal holder. They were then soldered in an air muffle furnace under differ-ent bonding conditions using flux (Weller T0051383199) and air-cooled to room temperature. A reference sample of the Cu-Sn-Cu system was prepared by bonding two Cu-Sn elec-troplated silicon chips in this study. The bonding procedures regarding time and temperature were selected to mimic wafer-level bonding conditions utilized for Cu–Sn bonds. Fig. 1 shows an illustration of the fabrication steps. The cross-sections of all samples were prepared using standard metallographic methods.

B. Microstructure examination and mechanical characterization

A JSM-6330F field emission scanning electron microscope (SEM; JEOL Ltd.) with a backscattered electron (BSE) detector was used to evaluate the interfacial and the phase composi-tion. The composition of phases was determined by averaging measurements from a minimum of five locations using EDX. Nano-indentation test was performed within the IMCs layers at the joint area of Co/Sn/Cu and Cu/Sn/Cu stacks using a CSM Instruments Nanoindentation tester. The mechanical properties of samples were measured using the continuous data of the applied load (P) and indenter displacement (h) during the test. The Nano-Indentation hardness (H) and reduced elastic modulus (Er) were calculated. The calculation of elastic modulus and hardness was based on the Oliver and Pharr Method.

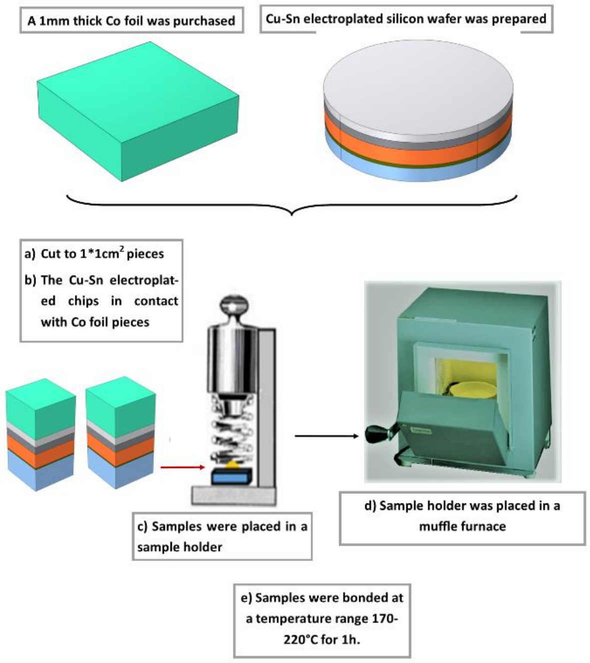

Figure 1. A schematic illustration of the fabrication steps in the present study.

III. RESULTS & DISCUSSION

A. Microstructural evolution

Figure 2-(a-d) show cross-sectional BSE micrographs of Cu–Sn–In SLID system in contact with Co bulk bonded at various bonding temperatures (160°C -250°C) for 1h. The SEM-EDX analysis for samples bonded at different bonding temperatures revealed that bonds comprised a void-free single $(Cu,Co)_6(Sn,In)_5$ phase. However, the Cu-Sn SLID joints is mostly composed of two intermetallic phases (Cu_3Sn and Cu6Sn5) and it can transform to a single Cu_3Sn IMC joint after a long bonding time and high bonding temperature [21][22]–[24]. On the other hand, the Cu-Sn-In SLID joints bonded at 200°C are composed of two intermetallic phases $Cu_3(Sn,In)$ and $Cu_6(Sn,In)_5$). In the higher bonding temperature, the Cu-Sn-In joints comprise a single Cu_3Sn and $Cu_3(Sn,In)$ phase, respectively. [1], [3]. It has been demonstrated that indium can stabilize the Cu_6Sn_5 phase and hinder the Cu_3Sn phase formation and correspondingly void formation [1].

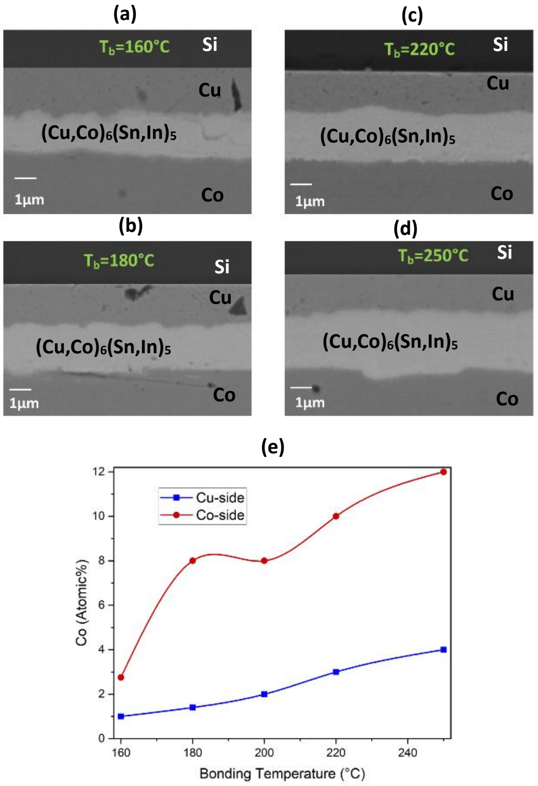

Figure 2. Cross sectional BSE-SEM images of Cu-Sn-In/Co joints formed at, (a) 160°C, (b) 180°C, (c) 220°C, and (d) 250°C for 1h, and (e) the average atomic percent of cobalt dissolved into $(Cu,Co)_6(Sn,In)_5$ phase (formed in the Cu- and Co-sides) as a function of bonding temperature.

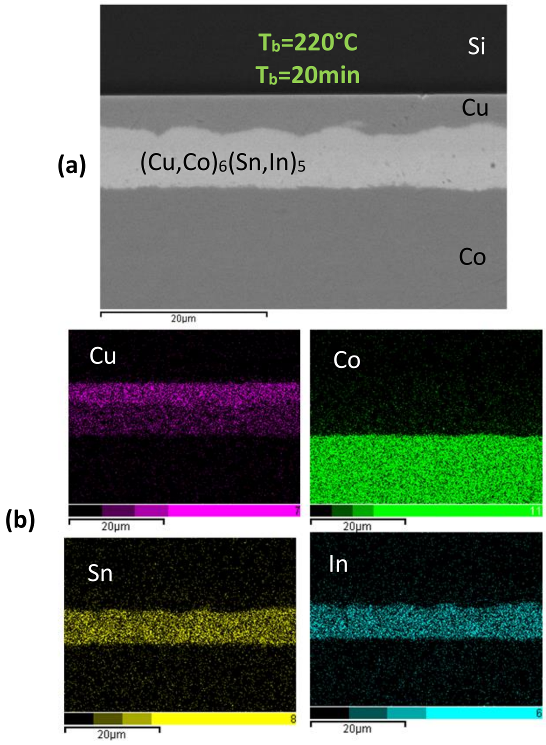

Figure 3. (a) The cross-sectional BSE-SEM image, and (b) the EDX elemental mapping of Cu-Sn-In/Co joint formed at 220°C for 20min.

Nonetheless, Cu_3Sn (which is always followed by void formation) will still form at 200°C in the bond area.

Our results revealed that Co significantly impacts the IMCs formed in the Cu-Sn-In SLID system. A void-free single $(Cu,Co)_6(Sn,In)_5$ phase joint can be obtained by utilizing Co as contact metallization for the Cu-Sn-In SLID system. It can offer several advantages for wafer-level packaging of MEMS/MOEMS devices: 1) Higher mechanical reliability as the joint is void-free and no phase transformation will occur during bonding, 2) A high electromigration resistance of microbumps by obtain-ing a void-free single-phase joint [25]–[28], and 3) applicability of the Cu-Sn-In/Co SLID system for temperature-sensitive devices, the bonding temperature can be as low as 160°C. Figure 2-e demonstrates the average atomic percent of cobalt dis-solved into $Cu_6(Sn,In)_5$ phase (formed in the Cu- and Co-sides) as a function of the bonding temperature. The Co content in $Cu_6(Sn,In)_5$ increased by rising the bonding temperature. The average Co content in $Cu_6(Sn,In)_5$ IMC formed in the Cu- and Co-sides were 1at% and 2.8at%, and 3at% and 11.8at% at a bonding temperature of 160°C and 250°C, respectively.

Figure 3 shows the cross-sectional BSE-SEM images and the EDX elemental mapping of the Cu-Sn-In/Co joint formed at 220°C for 20 minutes. The SEM_EDX analysis revealed that all the liquid Sn was consumed during the bonding, even though the bonding time was short compared to the SLID wafer-level bonding condition. A void-free single $(Cu,Co)_6(Sn,In)_5$ phase was identified in the bond area. The EDX maps show a uniform distribution of Cu, Sn, and In in the bond area. However, the Co signal is stronger in the Co-side compared to the Cu-side. The Co content in the $Cu_6(Sn,In)_5$ was measured to be 1at% and 5at% in the Cu- and Co-sides, respectively. It has been shown that Cu-Sn, Cu-Sn-In, and Co-Sn-Cu SLID systems need a longer bonding time to obtain fully IMCs joint [1]–[3], [9], [22], [24], [29] compared to the Cu-Sn-In/Co SLID joint studied in the current work. Employing Co as a contact metallization for low-temperature Cu-Sn-In SLID systems shortens the bonding time and bonding temperature. Hence, the induced stresses during bonding will be decreased, and as a result, the mechanical reliability of the joint can be enhanced.

B. *Mechanical characterization*

Figure 4-a shows the cross-sectional BSE micrographs of Cu-Sn-In/Co joint bonded at 200°C for 1h with marks of the nanoindentations. The nanoindentations were done at the joint area where $(Cu,Co)_6(Sn,In)_5$ IMC was identified. After the nanoindentation test, EDX analysis was done to ensure that the indentation lied completely within $(Cu,Co)_6(Sn,In)_5$ IMC. The indentation load-displacement curves of three different points in the $(Cu,Co)_6(Sn,In)_5$ are presented in Figure 5-b. The nanoindentation hardness (H), reduced elastic modulus (Er), and Young's modulus (Ei) were calculated based on the Oliver and Pharr Method and are listed in Table 1. The ratio of Young's modulus to hardness (Ei/H) defines the fraction of plastic deformation in the total deformation during indentation (δH), which can be used as a plasticity characteristic of brittle mate-rials. A high E/H value implies better plasticity for IMCs, while low E/H indicates brittleness [30]–[33]. Results indicated that $(Cu,Co)_6(Sn,In)_5$ shows higher Ei/H values and, subsequently, better plasticity than the Cu_6Sn_5 phase. The EDX analysis demonstrated that the metals (Cu, Co, Sn, and

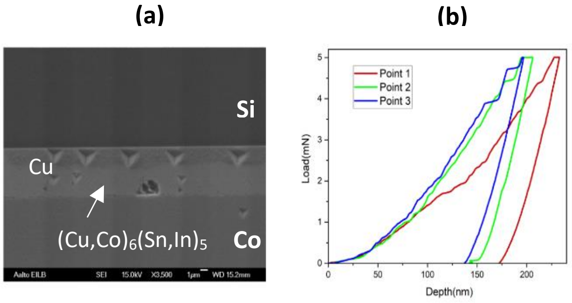

Figure 4. (a) BSE-SEM image of indents on Cu-Sn-In/ Co joint bonded at 200 C for 1h, and (b) the indentation load displacement curves of three different points in the bond area.

In) contents varied in the different points of the bond area. The nanoindenta-tion test results showed that once the Co content (at%) increased from 2.1 in point 1 to 6.2 in point 3 both Young's modulus and hardness values increased. On the other hand, by increasing the Cu/In ratio in $(Cu,Co)_6(Sn,In)_5$ (from point 1 to 2) both Young's modulus and hardness values increased. As a summary, the highest Ei/H and plasticity was measured for $(Cu,Co)_6(Sn,In)_5$ IMC with Cu(at%)/(Sn+In)(at%) and Sn(at%)/In(at%) close to 50%.

Table 1. The nanoindentation hardness (H), reduced elastic modulus (Er), and Young's modulus (Ei) of $(Cu,Co)_6(Sn,In)_5$ and Cu6Sn5 obtained from this study.

	Point1	**Point2**	**Point3**	**Cu_6Sn_5**
H (GPa)	4.6	5.9	6.6	6.7±0.5
Er (Gpa)	95.5	113.1	112.0	103.7±0.4
Ei (GPa)	104.2	125.5	124.1	114.1±1
Ei/H	22.6	21.3	18.8	17
Cu (at%)	49.1	57.6	48.9	55.3
Co (at%)	2.1	2.9	6.2	0
Sn (at%)	21.0	13.9	23.8	44.7
In (at%)	27.8	25.6	21.1	0

IV. CONCLUSSION

To conclude, this work elaborated on both microstructural and the mechanical characterization of the Cu-Sn-In/Co SLID joints bonded at various temperatures (160-250°C) for 1h. The SEM-EDX analysis demonstrated that the bond-ing areas of all samples were composed of a single $(Cu,Co)_6(Sn,In)_5$ phase, and the joints showed high bond quality (void- and crack-free). The results showed that Co has a significant impact on the stabilization of the $Cu_6(Sn,In)_5$ phase and inhibition of the Cu_3Sn phase evolution and subsequent void formation. Furthermore, we obtained a fully IMC joint of the Cu-Sn-In/Co SLID system at 220°C for a bonding time as short as 20 minutes. Hence, utilizing Cu-Sn-In/Co SLID system for MEMS/MOEMS packaging provides an advantage due to its significantly reduced processing time compared to Cu-Sn and Cu-Sn-In SLID systems. Consequently, the induced thermal stress during bonding can be diminished. In addition, based on the nanoindentation analysis, the joint's mechanical properties improved com-pared to the Cu-Sn SLID system. The Young's modulus to hardness ratios $(Cu,Co)_6(Sn,In)_5$ phase showed higher val-ues compared to pure Cu_6Sn_5 IMC. Utilizing Cu-Sn-In/Co SLID system instead of Cu-Sn and Cu-Sn-In SLID systems benefits the MEMS/MOEMS packaging by 1) reducing the bonding temperature and bonding time, 2) achieving a void-free single $(Cu,Co)_6(Sn,In)_5$ phase joint, and 3) enhancing the mechanical properties.

ABBREVIATIONS

SLID, solid liquid interdiffusion; IMC, intermetallic compound; MEMS, microelectromechanical systems; MOEMS, mi-cro-opto-electromechanical systems; FE-SEM, field emission scanning electron microscope; EDX, energy-dispersive X-ray spectroscopy.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] V. Vuorinen, H. Dong, G. Ross, J. Hotchkiss, J. Kaaos, and M. Paulasto-Kröckel, "Wafer Level Solid Liquid Interdiffusion Bonding: Formation and Evolution of Microstructures," Journal of Electronic Materials, vol. 50, no. 3. pp. 818–824, 2021.

[2] V. Vuorinen, G. Ross, A. Klami, H. Dong, and M. Paulasto-Kröckel, "Demonstrating 170◦C Low Temperature Cu-In-Sn wafer level Solid Liquid Interdiffusion Bonding," IEEE Trans. Components, Packag. Manuf. Technol., vol. 12, no. 3, 2022.

[3] J. Hotchkiss et al., "Study of Cu-Sn-In system for low temperature, wafer level solid liquid inter-diffusion bonding," Proc. - 2020 IEEE 8th Electron. Syst. Technol. Conf. ESTC 2020, 2020.

[4] T. T. Luu, N. Hoivik, K. Wang, K. E. Aasmundtveit, and A. S. B. Vardøy, "Characterization of Wafer-Level Au-In-Bonded Samples at Elevated Temperatures," Metall. Mater. Trans. A Phys. Metall. Mater. Sci., vol. 46, no. 6, pp. 2637–2645, 2015.

[5] L. Deillon, A. Hessler-Wyser, T. Hessler, and M. Rappaz, "Solid-liquid interdiffusion (SLID) bonding in the Au-In system: Experimental study and 1D modelling," J. Micromechanics Microengineering, vol. 25, no. 12, 2015.

[6] Y. Lai, S. Chen, X. Ren, Y. Qiao, and N. Zhao, "Solid–liquid Interdiffusion Bonding of Cu/Sn/Ni Micro-joints with the Assistance of Temperature Gradient," Acta Metall. Sin. (English Lett., no. 0123456789, 2022.

[7] X. F. Tan, Q. Gu, M. Bermingham, S. D. McDonald, and K. Nogita, "Systematic investigation of the effect of Ni concentration in Cu-xNi/Sn couples for high temperature soldering," Acta Mater., vol. 226, p. 117661, 2022.

[8] N. S. Bosco and F. W. Zok, “Critical interlayer thickness for transient liquid phase bonding in the Cu-Sn system,” Acta Mater., vol. 52, no. 10, pp. 2965–2972, 2004.

[9] F. Emadi, V. Vuorinen, H. Dong, G. Ross, and M. Paulasto-Kröckel, “Investigation of the microstructural evolution and detachment of Co in contact with Cu–Sn electroplated silicon chips during solid-liquid interdiffusion bonding,” J. Alloys Compd., vol. 890, p. 161852, 2022.

[10] Y. S. Chiu and C. R. Kao, “Microstructure Evolution of Cu/In/Cu Joints after Solid-Liquid Interdiffusion,” Proc. - Electron. Components Technol. Conf., vol. 2018-May, pp. 890–895, 2018.

[11] Y. Tian, N. Wang, Y. Li, and C. Wang, “Mechanism of low temperature Cu-In Solid-Liquid Interdiffusion bonding in 3D package,” ICEPT-HDP 2012 Proc. - 2012 13th Int. Conf. Electron. Packag. Technol. High Density Packag., pp. 216–218, 2012.

[12] Y. S. Chiu, H. Y. Yu, H. T. Hung, Y. W. Wang, and C. R. Kao, “Phase formation and microstructure evolution in Cu/In/Cu joints,” Microelectron. Reliab., vol. 95, no. September 2018, pp. 18–27, 2019.

[13] D. Q. Yu et al., “Wafer-level hermetic bonding using Sn/In and Cu/Ti/Au metallization,” IEEE Trans. Components Packag. Technol., vol. 32, no. 4, pp. 926–934, 2009.

[14] S. W. Chen, T. C. Yang, J. M. Lin, and T. Y. Huang, “Interfacial reactions in the Co/In/Cu and Ni/In/Cu samples,” J. Taiwan Inst. Chem. Eng., vol. 97, pp. 356–369, 2019.

[15] I. Panchenko, S. Bickel, J. Meyer, M. Mueller, and J. M. Wolf, “Characterization of low temperature Cu/In bonding for fine-pitch interconnects in three-dimensional integration,” Jpn. J. Appl. Phys., vol. 57, no. 2, 2018.

[16] Y. Hsieh, T. Shen, Y. Chein, and K. Chen, “Investigation of low temperature Cu/In bonding in 3D integration,” IEEE, pp. 383–386, 2015.

[17] S. K. Lin, T. Y. Chung, S. W. Chen, and C. H. Chang, “250 °C isothermal section of ternary Sn-In-Cu phase equilibria,” J. Mater. Res., vol. 24, no. 8, pp. 2628–2637, 2009.

[18] R. Roy, S. Sen, and S. K. Sen, “The formation of intermetallics in Cu/In thin films,” J. Mater. Res., vol. 7, no. 6, pp. 1377–1386, 1992.

[19] Y. C. Chen and C. C. Lee, “Indium-copper multilayer composites for fluxless oxidation-free bonding,” Thin Solid Films, vol. 283, no. 1–2, pp. 243–246, Sep. 1996.

[20] O. Golim, V. Vuorinen, N. Tiwary, R. Glenn, and M. Paulasto-Kröckel, “Low-temperature Metal Bonding for Optical Device Packaging,” 2021 23rd European Microelectronics and Packaging Conference and Exhibition, EMPC 2021. 2021.

[21] L. Sun, M. he Chen, L. Zhang, P. He, and L. sheng Xie, “Recent progress in SLID bonding in novel 3D-IC technologies,” J. Alloys Compd., vol. 818, p. 152825, 2020.

[22] K. Chu, Y. Sohn, and C. Moon, “A comparative study of Cn/Sn/Cu and Ni/Sn/Ni solder joints for low temperature stable transient liquid phase bonding,” Scr. Mater., vol. 109, pp. 113–117, 2015.

[23] Z. Yin, F. Sun, and M. Guo, “The fast formation of full - Cu 3 Sn solder joints in Cu / Sn / Cu system by thermal gradient bonding,” pp. 2146–2153, 2019.

[24] Z. Yin, F. Sun, and M. Guo, “The fast formation of Cu-Sn intermetallic compound in Cu/Sn/Cu system by induction heating process,” Mater. Lett., vol. 215, pp. 207–210, 2018.

[25] M. S. Park, S. L. Gibbons, and R. Arróyave, “Phase-field simulations of intermetallic compound growth in Cu/Sn/Cu sandwich structure under transient liquid phase bonding conditions,” Acta Mater., vol. 60, no. 18, pp. 6278–6287, 2012.

[26] V. Attari, S. Ghosh, T. Duong, and R. Arroyave, “On the interfacial phase growth and vacancy evolution during accelerated electromigration in Cu/Sn/Cu microjoints,” Acta Mater., vol. 160, pp. 185–198, Nov. 2018.

[27] Y. chen Liu, Y. si Yu, S. kang Lin, and S. J. Chiu, “Electromigration effect upon single- and two-phase Ag-Cu alloy strips: An in situ study,” Scr. Mater., vol. 173, pp. 134–138, Dec. 2019.

[28] Z. J. Morgan and Y. M. Jin, “Phase field modeling of pore electromigration in anisotropic conducting polycrystals,” Comput. Mater. Sci., vol. 172, p. 109362, Feb. 2020.

[29] H. Y. Zhao et al., “A Comparative Study on the Microstructure and Mechanical Properties of Cu6Sn5 and Cu3Sn Joints Formed by TLP Soldering With/Without the Assistance of Ultrasonic Waves,” Metall. Mater. Trans. A Phys. Metall. Mater. Sci., vol. 49, no. 7, pp. 2739–2749, 2018.

[30] J.-M. Song, B.-C. Hung, D. Tarng, C.-P. Hung, and K. Yasuda, “Relationship between Nanomechanical Response of Interfacial Intermetallic compound layers and Impact Reliability of Solder Joints,” Nanomaterials, vol. 10, no. 1456, pp. 539–547, 2020.

[31] Y. V. MILMAN, B. A. GALANOV, and S. I. CHUGUNOVA, “PLASTICITY CHARACTERISTIC OBTAINED THROUGH HARDNESS MEASUREMENT,” Acta Met. mater., vol. 41, no. 9, pp. 2523–2532, 1993.

[32] J. M. Song, W. C. Lu, and P. W. Chou, “Nanomechanical Responses of an Intermetallic Compound Layer in Transient Liquid Phase Bonding Using Indium,” J. Electron. Mater., vol. 49, no. 1, pp. 18–25, 2020.

[33] J. M. Song, Y. L. Shen, C. W. Su, Y. S. Lai, and Y. T. Chiu, “Strain rate dependence on nanoindentation responses of interfacial intermetallic compounds in electronic solder joints with Cu and Ag substrates,” Mater. Trans., vol. 50, no. 5, pp. 1231–1234, 2009.