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Investigation of the microstructural evolution and detachment of Co in contact with Cu–Sn electroplated silicon chips during solid-liquid interdiffusion bonding

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Abstract

Solid-liquid interdiffusion (SLID) bonding is one of the most promising novel methods for micro-(opto-)electromechanical system (MEMS/MOEMS) wafer-level packaging. However, the current SLID bonding solutions require the use of an electrochemical deposition method for MEMS/MOEMS wafers as well, which significantly complicates the process integration options. Hence, this work proposes Co as a potential option for compatible contact metallization on MEMS/MOEMS wafers to utilize mature Cu–Sn SLID bonding. The focus of this study is on gaining a fundamental understanding of the microstructural formation and evolution of Co substrates in contact with Cu–Sn electroplated silicon wafers and identifying possible failures of joints during bonding, which are prerequisites for guaranteeing devices’ manufacturability, functionality, and long-term reliability. The effect of bonding time and temperature on the microstructural evolution and phase formation of Co substrates in contact with Cu–Sn electroplated silicon chips was investigated. Moreover, a phase diagram of the Co–Cu–Sn ternary system was thermodynamically evaluated based on experimental data. Samples were successfully bonded at 250 °C for 1500 and 2000 s and at 280 °C for 1000 s. The main interfacial intermetallic compounds were identified as (Cu,Co)6Sn5, Cu3Sn, and (Co,Cu)Sn3. Co stabilized the high-temperature hexagonal (η) Cu6Sn5 phase down to room temperature. Bond detachment was observed when applying either a higher bonding temperature or a longer bonding time. Two critical factors that cause detachment during bonding were recognized: first, a change in thermodynamic equilibrium when exceeding the maximum allowed Co content in Cu6Sn5 formed adjacent to the CoSn3 phase and a discontinuous change in the Co content in the Cu6Sn5 grown on the Cu and Co sides; second, stress exerted due to the rapid growth of (Co,Cu)Sn3 between the Co substrate and (Cu,Co)6Sn5. Therefore, achieving successful bonding in the Co–Sn–Cu SLID system requires governing the amount of dissolved Co atoms in liquid Sn and the CoSn3 formation, both of which can be achieved by manipulating the relative thickness of the Co, Cu, and Sn layers. The observations and calculations in this work show that a prerequisite for obtaining successful bonding in the Co–Sn–Cu SLID system at 250 °C is a Co-to–Sn thickness ratio of 0.04 or less.

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1. Introduction

The unique nature of functional micro-(opto-)electromechanical systems (MEMS/MOEMS), such as sensors and actuators, calls for specific prerequisites: protecting fragile movable parts, providing a specific ambient, and making electrical paths to interact with the environment. In this regard, a combination of wafer-level bonding and through-silicon via technology has attracted considerable attention [1,2]. A wide range of wafer-level bonding has been applied in electronic manufacturing, including direct, anodic, glass frit, adhesive, and metal bonding (such as eutectic and solid-liquid interdiffusion [SLID] bonding). Wafer bonding processes using SLID bonding have attracted considerable interest, as they can form high remelting temperature intermetallic compound (IMC) joints at relatively low bonding temperatures. Other advantages of SLID bonding are fine-pitch bonding, well-defined metallurgy, substantial reduction of the bonding footprint compared to other bonding methods, and high current density capabilities. The SLID process is commonly based on a binary system with a high-temperature and a low-temperature melting metal [3–7]. Among various SLID bonding...
systems, such as Cu–Sn, Cu–In, Ag–Sn, Ag–In, Ni–Sn, Au–Sn, and Au–In, Cu–Sn-based metallurgy 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. Additionally, the manufacturing processes for Cu–Sn micro-joints are mature and easily available at a relatively low cost. Two main IMCs formed in Cu–Sn SLID bonding are Cu3Sn and Cu6Sn5, which have remelting temperatures of 676 and 415 °C, respectively [6–8]. The allotropic transformation from high-temperature hexagonal $\eta$-Cu6Sn5 to low-temperature monoclinic $\eta'$-Cu6Sn5 at a temperature of less than 186 °C and void formation due to the Cu3Sn phase formation deteriorate the mechanical properties of the joints [9–13]. Various metals, such as Ni, Au, In, and Zn, have been widely explored as the third elements for Cu–Sn SLID bonding systems to stabilize the high-temperature hexagonal $\eta$-Cu6Sn5 phase. Furthermore, elements such as Zn and Ni can suppress the Cu3Sn phase formation and subsequently void formation [9,14–23].

Regarding the wafer-level packaging of MEMS devices, typical process integration challenges are related to the chemical/electrochemical plating processes for the SLID interconnection materials without negatively impacting the sensitive MEMS structures or vice versa. It is necessary to protect the sensitive MEMS structures from either the wet-chemistry or plated metals during the deposition processes. Nowadays, research is focusing on single contact metallization or metallization stacks that could be manufactured with PVD (Physical vapor deposition) or CVD (Chemical vapor deposition) methods on MEMS device wafers. These must be complementary metal-oxide-semiconductor (CMOS)/MEMS-compatible and chemically compatible with SLID bonding metallurgies, which are applied on the cap wafers. Rautiainen et al. explored the possibilities of CMOS-compatible Pt metallization for single-layer contact material for Cu–Sn SLID bonding utilized on MEMS device wafers and found that Pt dissolves in Cu6Sn5 and stabilizes high-temperature hexagonal $\eta$-Cu6Sn5 down to room temperature. The presence of Pt also provides stable contact during aging [24]. However, like gold, platinum—as a noble metal—has a challenging etch process. Ni and Cu are widely used as contact metallization layers for soldering. However, the use of Ni and Cu for contact metallization for SLID bonding presents certain difficulties. For instance, Ni is challenging due to its fast oxidization [25], stresses exerted during thick layer sputtering, and the brittleness of the IMCs. Cu dissolves rapidly in Sn, and therefore a thick Cu layer is required.

Co is a promising metallization candidate for soldering joints due to its many favorable attributes, such as superior diffusion barrier capability, excellent thermal cycle fatigue, high electromigration resistance, acceptable wettability, and mechanical strength in solder joints [26–33]. Co substitutes the Cu atoms in Cu–Sn IMCs, promoting Cu6Sn5 phase formation, stabilizing the hexagonal Cu6Sn5 phase down to room temperature, refining the grain morphology, and suppressing the Cu3Sn phase formation and subsequent void formation [31,34–38].

IMCs formed in ternary or binary systems depend on the bonding conditions (bonding temperature and bonding time). For instance, a Co–Sn binary system has four stable phases at room temperature: Co3Sn, CoSn, CoSn2, and CoSn3. However, it is possible that only one or two phases are present in bonding areas, depending on factors such as bonding conditions, experimental setup, and additional elements [32,39]. Previous studies have examined various IMCs in the Cu–Sn–Co ternary system. Studying Cu–Sn–Co joints, Du et al. observed (Cu,Co)6Sn5, (Co,Cu)Sn, and (Co,Cu)Sn3 in the joint area, depending on the bonding temperature and time [38]. Because IMC properties have a substantial impact on the thermomechanical properties and reliability of SLID bonding, it is vital to understand
the type and thickness of IMCs formed in Co–Sn–Cu under various bonding conditions and optimize them to achieve highly reliable bonds.

Co can thus be considered a candidate for contact metallization in Cu–Sn SLID bonding on MEMS device wafers. However, before introducing a new metal for contact metallization in Cu–Sn SLID bonding, a comprehensive understanding of the interfacial reactions is of utmost importance. The IMCs evolving in the interfacial layer differ depending on factors such as varying thickness of the Cu and Sn layers and temperature. This work aimed to investigate the microstructural evolution of Co substrates in contact with 4-μm Sn/8-μm Cu electroplated silicon chips to explore the possibility of using Co for contact metallization for Cu–Sn SLID bonding on MEMS device wafers and to identify possible failures of joints during bonding.

2. Materials and methods

2.1. Specimen preparation

Co foil (purity: 99.99%, Goodfellow Ltd.) 1 mm in thickness was cut into pieces 1 × 1 cm in size. The pieces were mechanically ground to 2400 papers, cleaned with acetone, and air-dried before bonding. Fig. 1 shows an illustration of the fabrication steps. All samples were prepared on thermally oxidized (300-nm SiO2) 4” Si (100) wafers. A 60-nm-thick TiW adhesion layer was sputtered on the wafer, followed by sputtering of a 100-nm-thick Cu seed layer. Cu (8 μm) was electroplated using an NB Semiplate Cu 100 bath (NB Technologies), followed by 4-μm electroplated Sn using an NB Semiplate Sn 100 solution (NB Technologies). Cu–Sn metallized wafers were cut into 5 × 5 mm pieces. Finally, the prepared chips in contact with Co foil pieces were placed in a relatively large metal holder. They were then soldered in an air muffle furnace under different bonding conditions using flux (Weller T0051383199) and air-cooled to room temperature. The temperature increases versus the time for set furnace state aging at 150 °C for 1000 h.

Three bonding conditions were applied:

1) A bonding temperature of 250 °C and bonding times ranging from 1500 to 3000 s
2) A bonding temperature range of 280–320 °C for 1000 s
3) A bonding temperature of 250 °C for 1500 s, followed by solid-state aging at 150 °C for 1000 h.

The bonding time and temperature conditions were selected to mimic wafer-level bonding conditions for Cu–Sn bonds.

2.2. Microstructural analysis

A JSM-6330F field emission scanning electron microscope (SEM; JEOL Ltd.) with a backscattered electron (BSE) detector, an INCA X-ray imaging system (Oxford Instruments), a JIB-4700F focused ion beam (FIB; JEOL Ltd.) with upper secondary electron (USE) imaging, and a SmartLab X-ray diffractometer (Rigaku) equipped with a 9-kW rotating Cu anode source and a 2D single-photon counting pixel detector (HyPix-3000) were used for detailed microstructural analysis. For cross-section analysis using SEM and EDX, samples were prepared using standard metallographic methods. The composition of phases was determined by averaging measurements from a minimum of five locations using EDX. A detached sample soldered at 250 °C for 3000 s was selected for examination using high-resolution X-ray diffraction (XRD) and two-dimensional XRD (2D-XRD). Data were collected in a 2θ range of 25–85°.

2.3. Thermodynamic calculation

The calculation of phase diagrams (CALPHAD) method was used to construct a phase diagram of the ternary Co–Cu–Sn system. The system was thermodynamically evaluated based on binary thermodynamic descriptions [39–41] and experimental investigations of the ternary phase equilibria in a previous study [42] and in this work. The lattice stability of element i (i = Co, Cu, or Sn) refers to the enthalpy of its stable state at 298.15 K and 100 kPa, \( H^\text{stab}_i \), as recommended by Scientific Group Thermodata Europe [43]. Thermodynamic parameters of compounds in the binary systems were directly taken from relevant publications: Co–Cu according to Turchanin and Agraval [39], Co–Sn according to Jedlicková et al. [40], and Cu–Sn according to Dong et al. [41]. Regarding the ternary system, most binary compounds have the solubility of a third element, as reported by Chen et al. [42]. To describe the experimen
tal observations, proper sublattice-site models were defined based on an analysis of the experimental results, as well as the crystal structure of the relevant compounds. For instance, stoichiometric binary compounds exhibiting the solubility of the third element were treated as semi-binary compounds—for example, \((Co,Cu)_6Sn_5\) m. Binary compounds with a NiAs prototype crystal structure—that is, \(Co_4Sn_5\) HT and \(Cu_4Sn_5\) HT (HT: high temperature)—were treated as one phase with a sublattice model of \((Co,Cu)_6Sn_5\) HT: \((Co,Cu)_6Sn_5\) HT. There was also a ternary line compound—\(Co_3Cu_2Sn_5\)—in this ternary system, which was modeled as a stoichiometric compound. The thermodynamic parameters of the involved phases were evaluated accordingly. The obtained thermodynamic database can reproduce these experimentally determined phase equilibria.

3. Results

3.1. Growth of intermetallic phases between Co substrates and Cu-Sn electroplated silicon chips under various bonding conditions

The Cu–Sn–Co stacks were successfully bonded at 250 °C for 1500 and 2000 s and at 280 °C for 1000 s. Detachments occurred at 250 °C for 2500 s and at 300 and 320 °C for 1000 s. EDX was used to identify the elemental compositions of the interfacial IMC layers. Three phases were identified in the bonding zone: \((Cu,Co)_6Sn_5\), \(Cu_3Sn_2\) and \((Co,Cu)_3Sn_5\). Immediately after bonding, the \((Co,Cu)_6Sn_5\) phase grew separately from both the Cu–Sn and Co–Sn interfaces, and a thin layer of \(Cu_3Sn_2\) appeared between electroplated Cu and the \((Co,Cu)_3Sn_5\)IMC. In contrast, \((Co,Cu)_3Sn_5\) formed at higher temperatures and after longer bonding times, suggesting that its formation requires bonding at a higher temperature-time average. A comparison of the results of several samples suggested that the various bonding conditions provided similar microstructural evolution effects, the only difference being in the reaction kinetics. The Co content in the \((Cu,Co)_6Sn_5\) layer was 2 at% on average on the Cu side and between 4 and 8 at% on the Co side, depending on the bonding temperature and time. With an increase in either the temperature or the time, the Co content in \(Cu_3Sn_2\) formed on the Co side increased. The dissolved Co content in \((Cu,Co)_6Sn_5\) adjacent to \((Co,Cu)_3Sn_5\) was considerably higher in detached samples (~12 at%) than in successfully bonded samples.

The fracture surfaces of the sample prepared at 250 °C for 3000 s were analyzed. Top-view BSE images are shown in Fig. 3. The phases on the surfaces of the Co and Cu sides were identified as \((Cu,Co)_6Sn_5\). Most \((Cu,Co)_6Sn_5\) grains on the Cu side contained 2 at% of Co on average, while a few grains contained 5 at%. On the Co side, the Co content was 12 at% in most \((Co,Cu)_3Sn_5\) grains and 5 at% in a few grains. As shown in Fig. 3, when the Co content in \((Cu,Co)_6Sn_5\) increased, the grains became smaller and finer. This finding is in line
with previous investigations [37,44]. Moreover, the (Cu,Co)\(_6\)Sn\(_5\) grains with lower Co contents (2 and 5 at\%) exhibited a faceted structure with a diameter between 2.4 and 5 µm and a length between 4 and 9 µm. However, the grains containing 12 at\% of Co on the detached sample’s Co side had a significantly smaller size than those on the Cu side.

Fig. 4 shows a BSE image of an FIB polished sample (bonded at 250 °C for 2000 s) and a USE image from the cross-section area, shown with red arrows in the BSE image. The visible boundaries of (Cu,Co)\(_6\)Sn\(_5\) phase are indicated by dashed red lines in the USE image. The Co content in (Cu,Co)\(_6\)Sn\(_5\) increased from 2.4 to 8.1 at\% across the reaction area from the Cu to the Co side. Sharp edges were visible in the Sn/(Cu,Co)\(_6\)Sn\(_5\) phase boundaries, especially on the Cu side, indicating a hexagonal crystal structure of (Cu,Co)\(_6\)Sn\(_5\). Morphology observations suggested that (Cu,Co)\(_6\)Sn\(_5\) formed on both the Cu and Co sides was faceted, with diameters between 2.1 and 4.6 µm.

3.2. Evolution of intermetallic phases between Co substrates and Cu–Sn electroplated silicon chips during solid-state aging

Cross-sectional BSE micrographs of the samples bonded at 250 °C for 1500 s before and after aging at 150 °C for 1000 h are illustrated in Fig. 5. As discussed in Section 3.1, during bonding at 250 °C for 1500 s, the only IMCs observed were a layer of (Cu,Co)\(_6\)Sn\(_5\), which

Fig. 2. Cross-sectional BSE SEM images of Cu–Sn–Co joints formed at (a) 280 °C, (b) 300 °C, and (c) 320 °C for 1000 s and at 250 °C for (d) 1500 s, (e) 2000 s, and (f) 3000 s.

Fig. 3. Top-view BSE image of a detached sample prepared at 250 °C for 3000 s (a) Cu side and (b) Co side.
grew on both the Cu and Co sides, and a thin layer of Cu$_3$Sn between Cu and (Cu,Co)$_6$Sn$_5$. No new phase was observed after annealing at 150 °C for 1000 h. The (Cu,Co)$_6$Sn$_5$ phase layers formed on the Cu and Co sides continued to grow and created an almost continuous vertical phase structure between the Co substrate and electroplated Cu on the silicon chip. Only a small amount of Sn remained on the Co side after long-time annealing. Notably, (Co,Cu)Sn$_3$ did not nucleate during the aging time.

### 3.3. Phase and crystal orientation identification using XRD and 2D-XRD

To better identify the IMCs formed at the bonding interface, XRD analysis was performed. Fig. 6 shows the XRD diffractograms of Co–Sn–Cu joints prepared at 250 °C for 3000 s before and after aging at 150 °C for 1000 h (examined from the top surface of the detached Cu and Co sides). Three IMCs were identified as hexagonal Cu$_6$Sn$_5$ and orthorhombic Cu$_3$Sn on the Cu side and hexagonal Cu$_6$Sn$_5$ and CoSn$_3$ on the Co side. It should be noted that CoSn$_3$ has two crystal structures: $\alpha$ and $\beta$. As distinguishing between these two crystal structures using XRD diffractograms is difficult, we did not identify the crystal structure of CoSn$_3$ IMCs formed at the bonding interface. The XRD results were in good agreement with the EDX analysis. Peaks related to the unreacted Cu and Si wafer were also identified. According to the XRD diffractograms, aging did not cause a phase transformation of Cu$_6$Sn$_5$ from a hexagonal crystal structure to a monoclinic crystal structure.

As Cu$_6$Sn$_5$ has various Co contents, it is essential to study the effect of Co on its crystal orientations, which can impact the thermomechanical properties of the joints. One way to identify the crystal orientations is to analyze wide-area diffraction space maps, on which 2D diffraction patterns are manipulated and interpreted. On a wide-area diffraction space map, the horizontal and vertical axes show a chi angle ($\chi$: diffraction vector tilt angle) and 2θ, respectively. The diffraction maps indicate the direction of the measured crystallographic planes, revealing the preferential crystal orientation of a sample. In this work, samples were scanned in a chi angle range of $-10$–$50^\circ$. Fig. 7 displays the wide-area diffraction maps of Co–Sn–Cu joints on the Cu and Co sides prepared at 250 °C.
(a)

(b)

Fig. 7. Wide-area diffraction maps of Co–Sn–Cu joints bonded at 250 °C for 3000 s. Top-view analysis of (a) the Cu side and (b) the Co side.

for 3000 s. The diffracted lines related to Cu6Sn5 are marked by Ⅰ. Diffraction lines of the basal plane (0001), which are indicated by dotted white arrows, were not observed on the studied maps. Hence, it can be concluded that the crystals were orientated with their c-axis in the sample’s in-plane direction. The results indicate that there was no noticeable crystal orientation difference between (Cu,Co)6Sn5 IMCs containing 12 and 2 at% of Co on the Co and Cu sides, respectively.

4. Discussion

The experimental results show that the reaction products of the Co substrates in contact with the Cu–Sn electroplated silicon chips were (Cu,Co)6Sn5, (Co,Cu)Sn3, and (Cu,Co)3Sn, depending on the bonding temperature and time. A schematic illustration of the elements’ diffusion direction and IMC formation in the observed sequence based on the experimental observations is shown in Fig. 8.

First, both Cu and Co dissolved rapidly in liquid Sn and moved in opposite directions. Subsequently, the (Cu,Co)6Sn5 IMC (layer I) nucleated and grew at both the Co/Sn and Cu/Sn interfaces (Fig. 8a).

Next, a thin layer of Cu3Sn with negligible Co content (layer II) formed between Cu and (Cu,Co)6Sn5 (Fig. 8b). Meanwhile, Sn diffused through (Cu,Co)6Sn5 on the Co side, and consequently, (Co,Cu)Sn3 (layer III) formed between Co and (Cu,Co)6Sn5 (Fig. 8c). The findings suggest that the (Co,Cu)Sn3 IMC requires a higher bonding temperature and/or a longer bonding time to form than the (Cu,Co)6Sn5 IMC. According to Tian et al., CoSn3 growth is more temperature sensitive than Cu6Sn5 growth [41]. Furthermore, Wang et al. reported that CoSn3 formation at the initial bonding stages was significantly suppressed when a Co diffusion barrier deposited on the Cu substrate contacted SAC solder compared to pure Sn solder [38]. This suggests that Cu in solder delays the dissolution of Co atoms and, consequently, the formation of a CoSn3 IMC. Once the Cu content near the Co layer decreased due to (Cu,Co)6Sn5 IMC formation, CoSn3 became the dominant phase. The rapid formation of (Co,Cu)6Sn5 compared to (Co,Cu)Sn3 is in line with Chen et al.’s conclusion that Cu diffusivity in Sn is considerably higher than Co diffusivity and that the maximum solubility of Co in liquid Sn is 0.04 wt%. Therefore, it can be concluded that the accumulation of Cu close to the Sn/Co interface inhibited Cu dissolution in Sn to form (Co,Cu)Sn3, whose formation obviously required a significantly higher amount of dissolved Co than that of (Cu,Co)6Sn5. The formation of (Co,Cu)6Sn5 at the Co/Sn interface led to the consumption of Cu adjacent to the Co substrate. At the subsequent stages, Sn passed through (Cu,Co)6Sn5 and reacted with Co to form (Co,Cu)Sn3, as shown in Fig. 8c and d.

Fig. 8d shows fully IMC joints with three IMC layers: a thin layer of Cu3Sn, thick layers of (Cu,Co)6Sn5 on both the Cu and Co sides, and a thick layer of (Co,Cu)Sn3 detached from the center of interfacial IMC layers. It is noteworthy that solder volumes, used in three-dimensional (3D) integration technology, will become ever smaller, and joints show a trend toward fully IMC joints because of miniaturization. Unlike joints including IMCs and unreacted Sn between them, fully IMC joints pose more reliability challenges during fabrication and operation due to the brittle nature of IMCs, which cannot accommodate the stresses exerted on the joints. For instance, Wang et al. [26] and Du et al. [45] observed the same IMC layers—Cu3Sn, (Cu,Co)6Sn5, and (Co,Cu)Sn3—in Co–Sn–Cu stacks. They used a thick layer of Sn (≥ 70 μm), a large fraction of which was unreacted after bonding. Conversely, in this work, all Sn was consumed during bonding in the detached samples.

To investigate long-term reliability performance under high-temperature operating conditions, the samples bonded at 250 °C for 1500 s, which contained (Cu,Co)6Sn5 and unreacted Sn, were aged at 150 °C for 1000 h. The joint was converted to an almost fully IMC joint after aging, with no fractures or cracks. It should be noted that unlike in detached samples, a CoSn3 phase was not detected in these samples. A large fraction of the (Cu,Co)6Sn5 IMCs formed at a low temperature (150 °C), below the transformation temperature of hexagonal crystal structures to monoclinic structures. Moreover, the Co content in (Cu,Co)6Sn5 was lower in these samples than in the detached samples, which can also affect the orientation of the crystals.

Regarding the use of Co for contact metallization for Cu-Sn SLID bonding, it is of prime importance to identify the risks that could lead to failure during fabrication and operation. Considering the differences between successfully bonded and detached samples, four possible reasons for detachment were identified:

1) The (Cu,Co)6Sn5 phase transformation from a high-temperature hexagonal crystal structure to a low-temperature monoclinic crystal structure during cooling.
2) The different crystal orientations of (Cu,Co)6Sn5 formed on the Co and Cu sides.
3) The rapid growth of IMCs and volumetric changes during IMC formation.
4) The change in the local thermodynamic equilibria.

Based on the XRD results, (1) and (2) seem implausible, as (Cu,Co)6Sn5 on both sides was hexagonal and retained this structure after long-term aging. Therefore, no phase transformation occurred during cooling. Moreover, crystal orientation observations showed that (Cu,Co)6Sn5 growth on the Cu and Co sides had similar growth
The thicknesses and relative fractions of IMCs as functions of bonding time and temperature are shown in Fig. 9. With an increase in the temperature or time, the thickness of (Cu,Co)$_6$Sn$_5$ and (Co,Cu)Sn$_3$ formed on the Co side and the total thickness of the IMCs increased. The thickness of the (Co,Cu)Sn$_3$ IMC and the total IMC layer drastically increased at higher bonding temperatures and longer bonding times. The IMC thickness as a function of bonding time at 250 °C indicated that as the bonding time exceeded 2000 s, the (Co,Cu)Sn$_3$ growth rate increased significantly. Also, the (Co,Cu)Sn$_3$ phase started to grow rapidly at temperatures above 300 °C (the lowest bonding temperature at which detachment occurred with a bonding time of 1000 s). It can be concluded that the (Co,Cu)Sn$_3$ IMC grew rapidly once it nucleated. A rapid growth of (Co,Cu)Sn$_3$ has been reported to occur due to many diffusion paths available to elements in the (Co,Cu)Sn$_3$ crystal structure, which has low density [46]. As a result, Sn atoms diffused rapidly through both (Cu,Co)$_6$Sn$_5$ and (Co,Cu)Sn$_3$ to reach the Co substrate surface and grow further. The rapid growth of CoSn$_3$ has been discussed extensively [47–49].

Considering the bonding time and temperature of detached samples and the growth of CoSn$_3$, it can be concluded that the rapid growth of (Co,Cu)Sn$_3$ and total IMCs coincided with the detachment. As shown in Fig. 9a and b, the (Co,Cu)Sn$_3$ fraction was above 25% in all detached samples. In this work, the volumetric change due to (Co,Cu)Sn$_3$ formation is considered the same as that for CoSn$_3$ formation from liquid Sn and solid Co, as the Cu content in CoSn$_3$ was not particularly noticeable. Therefore, the shrinkage of joints prepared at 250 °C for 3000 s caused by the formation of (Co,Cu)Sn$_3$ was calculated to be 13% using the following equation:

$$\Delta V_{\%}(\text{Cu}_6\text{Sn}_5) = \frac{(M_{\text{Cu}_6\text{Sn}_5} \rho_{\text{Cu}_6\text{Sn}_5}) - (M_{\text{Co}} \rho_{\text{Co}} + 3M_{\text{Sn}} \rho_{\text{Sn}})}{(M_{\text{Co}} \rho_{\text{Co}} + 3M_{\text{Sn}} \rho_{\text{Sn}})} \times 100 \quad (1)$$

Besides, the volumetric change of the formation of (Cu,Cu)$_6$Sn$_5$ was calculated to be 10% shrinkage using Eq. (2):

$$\Delta V_{\%}(\text{Cu}_6\text{Sn}_5) = \frac{(M_{\text{Cu}_6\text{Sn}_5} \rho_{\text{Cu}_6\text{Sn}_5}) - (6M_{\text{Cu}} \rho_{\text{Cu}} + 5M_{\text{Sn}} \rho_{\text{Sn}})}{(6M_{\text{Cu}} \rho_{\text{Cu}} + 5M_{\text{Sn}} \rho_{\text{Sn}})} \times 100 \quad (2)$$

A 13% shrinkage due to the rapid formation of a thick layer of (Co,Cu)Sn$_3$ along with 10% shrinkage owing to (Cu,Co)$_6$Sn$_5$ formation can exert considerable stress on the system. Since there was no soft material, such as Sn, in the interfacial layer to absorb the stress, the brittle IMC layer could not withstand the stress, and detachment could occur. However, this high shrinkage estimation is for the worst-case scenario, since in reality, applying pressure during bonding leads to a nonconstant volume until IMCs from both sides meet each other and fix the height of the bond.

### 4.1.1. Phase equilibrium

Fig. 10 shows the calculated isothermal sections of the Cu–Sn–Co ternary system at 250 and 150 °C using the thermodynamic database created in this work. Based on the results, the maximum solubility of Co in the Cu$_6$Sn$_5$ phase is ~20 and 13 at% at 250 and 150 °C, respectively, which equilibrates to CoSn and Cu$_3$Sn. Cu$_6$Sn$_5$ containing 8–15 at% of Co at 250 °C and 8–11 at% of Co at 150 °C can be in equilibrium only with the CoSn$_2$ and Cu$_3$Sn phases. However, the CoSn$_3$ phase can be in equilibrium with Cu$_6$Sn$_5$ containing 7–8 at% of Co at 250 °C and 5–8 at% of Co at 150 °C. As discussed in Section 3.1, Cu$_6$Sn$_5$ with 12 at% of Co was adjacent to (Co,Cu)Sn$_3$ in detached samples. Therefore, the Co content in Cu$_6$Sn$_5$ exceeded the local phase equilibrium condition, whereas the Co contents in IMCs formed in samples successfully bonded and annealed for 1000 s were within the range of equilibrium. The dotted line I in Fig. 10 shows the observed reaction sequence for the successfully bonded samples. Two possible reaction sequences for fully IMC joints at a bonding temperature of 250 °C are illustrated in Fig. 10 with dotted lines II and III (either Cu$_6$Sn$_5$ with 12 at% of Co in equilibrium with CoSn$_3$ or Cu$_6$Sn$_5$ with 7–8 at% of Co in equilibrium with CoSn$_3$).

![Fig. 8. Schematic illustration of element diffusion and IMC formation.](image-url)
Fig. 9. (a) IMC thickness as a function of temperature for a bonding time of 1000 s (b) IMC fraction as a function of temperature for a bonding time of 1000 s (c) IMC thickness as a function of time at a bonding temperature of 250 °C. (d) IMC fraction as a function of time at a bonding temperature of 250 °C.

Fig. 10. Calculated isothermal section of Cu-Co-Sn at (a) 250 °C and (b) 150 °C.
Changes in the Co contents in Cu6Sn5 by moving from the Cu to the Co side in a successfully bonded sample at 250 °C for 1500 s and a detached sample prepared at 250 °C for 3000 s.

3000 s were calculated to be 160 and 900 nm, respectively, using the following equation:

\[
X_{\text{co}} = \frac{M_{\text{Cu}}}{\rho_{\text{Cu}}} \times \left[ \frac{\rho_{\text{Cu6Sn5}} \times X_{\text{CuSn}}}{M_{\text{CuSn}}} + \frac{6 \times \text{at.} \% \text{Co} \times \rho_{\text{CoSn3}} \times X_{\text{CuSn}}}{M_{\text{CoSn3}}} \right] 
\]

where \(M_x\), \(\rho_x\), and \(X_x\) are the molar weight, density, and thickness of component \(x\).

5. Conclusion

This work investigated the microstructural evolution of a Co substrate in contact with a Cu–Sn electroplated silicon chip to gain a deeper understanding of the potential use of Co for contact metallization for Cu–Sn SLID bonding. The results demonstrated that three phases were formed in the Cu–Sn–Co stack at bonding temperature ranges of 280–320 °C for 1000 s and 250 °C for 1500–3000 s: (Cu,Co)6Sn5, (Co,Cu)Sn3, and (Co,Co)Sn3. The bonding time and temperature determined which of these phases appeared in the interconnection microstructure. Co (2–12 at%) dissolved in Cu6Sn5 stabilized the high-temperature hexagonal crystal structure of Cu6Sn5 down to room temperature, which is consistent with the thermodynamic calculation results. The crystal orientations of Cu6Sn5 with low and high Co contents were similar. However, a higher Co content had a significantly greater effect on the refinement of the grains. The (Co,Cu)Sn3 IMC required a higher bonding temperature-time average to form than (Cu,Co)6Sn5. Once (Co,Cu)Sn3 formed, it grew rapidly. The content of Co dissolved in (Co,Cu)6Sn5 exceeded the condition of maximum Co content in Cu6Sn5 for thermodynamic equilibrium with (Co,Cu)Sn3. Furthermore, a local phase equilibrium was observed at the interface of (Co,Co)6Sn5 grown on the Cu and Co sides in detached samples. In higher temperature-time averages, a higher (Co,Cu)Sn3 growth rate and the formation of local nonequilibrium phases caused joints to detach.

Co can be deposited by physical vapor deposition, and it is CMOS/MEMS-compatible. Furthermore, this study shows that it is chemically compatible with the Cu–Sn system. Our experimental work and thermodynamic calculation results suggest that Co is excellent for contact metallization for Cu–Sn SLID bonding only if its thickness is limited to the critical value to ensure that its content in the Cu6Sn5 IMC remains low and rapid growth of CoSn3 is prevented. This means that the amount of dissolved Co must be controlled to achieve successful bonding in a Cu–Sn–Co SLID bonding system. According to the calculations in this study, Co and Sn must have an XCo-to-XSn thickness ratio of ≤ 0.04.

CRediT authorship contribution statement

M. Paulasto-Kröckel: Supervision, Conceptualization, Writing – review & editing. V. Vuorinen: Project administration, Conceptualization, Writing – review & editing. G. Ross: Writing – review & editing, Formal analysis. H. Dong: Thermodynamic
modeling. Validation. F. Emadi: Formal analysis, Investigation, Writing – original draft, Visualization.

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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