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# Microstructure and mechanical property of Cu/In–45Cu/Ni solder joints formed by transient liquid phase bonding

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**In this paper, the microstructure and the shear property of Cu/In–45Cu/Ni solder joints by transient liquid phase were studied, and the intermetallic compounds (IMCs) growth mechanism was investigated. The results showed that the IMCs volume ratio of solder joints was increased firstly and then decreased with increasing bonding time, and the IMCs volume ratio reached its maximum value of 95.8% at 60 min. The Cu interfacial IMC of the solder joint with dense microstructure was $Cu_2In$ phase at 60 min, and the Ni interfacial IMC was $Ni_3In_7$. The maximum shear strength of solder joints was obtained at 60 min, which is 15.21 MPa. The shear fracture appeared honeycomb structure, and the fracture occurred at the phase interface of $Ni_3In_7/Cu_{11}In_9$. The thickness of the interfacial IMCs and the white IMCs around the Cu particles (Cu@IMC) was increased continuously with increasing bonding time, and thus, the interconnection of Cu–Ni substrates was realized ultimately.**

## Introduction

The wide band gap semiconductor materials are widely used in aerospace, petrochemical, rail transportation, clear energy, and many other fields due to its excellent electronic, physical, chemical, and mechanical properties [1]. The third-generation wide band gap semiconductor materials represented by SiC and GaN have become the most important semiconductor materials for manufacturing high-frequency power electronic devices, short-wavelength optoelectronic devices, and high-temperature and radiation-resistant devices, which can be used up to 300 °C [2, 3]. However, the electronic interconnection materials tend to fracture in high-temperature environment, and the reliability of interconnect solder joints in electronic products has become a key issue affecting system reliability [4, 5]. Therefore, the development of packaging technologies and connection materials used at high temperature is of great significance to the electronic packaging industry [6]. In recent years, transient liquid phase (TLP) bonding as a new type of packaging technology has attracted more and more attention due to its simple process and low cost [7, 8, 9].

As a superior substrate material, Cu is widely used in the electronic packaging field due to its excellent electrical conductivity, good thermal conductivity, and strong corrosion resistance. The fast reaction rate between Cu and solders results in the rapid growth of intermetallic compounds (IMCs) at the interface, and then, the reliability of solder joints is degraded dramatically [10]. Ni is frequently used as the diffusion barrier in under bump metallurgy on the chip side to inhibit the rapid formation of interfacial IMCs during soldering [11, 12]. Therefore, the connection of the Cu/Ni sandwich structure would be encountered in electronic devices, and the reactions of Cu/Ni joints during soldering crucially determine the reliability of devices.

Lots of researches were carried out on the microstructure and mechanical properties of Cu/Ni TLP joints by using Sn-based solders, such as pure Sn [13, 14, 15], Sn–0.7Cu [16], Sn–Ag [17], and Sn–9Zn [18]. Dong [13] found that the IMCs transformed from $(Cu, Ni)_6Sn_5$ into $Cu_3Sn$ on the Cu interface from 30 to 120 min. The shear strength of the Cu/Sn/Ni solder joint was 49.8 ± 0.3 MPa at 120 min, and the shear fracture was inclined to occur in the area of $(Cu, Ni)_6Sn_5$ grains with the coarse rounded shape. Mo [14] pointed out that the IMCs in the Cu/Sn/Ni solder joints were $(Cu, Ni)_3Sn$ on the Cu substrate and $(Cu, Ni)_6Sn_5$ IMCs on the Ni substrate at 240 °C, and the $(Cu, Ni)_6Sn_5$ was converted to $(Cu, Ni)_3Sn$ with the bonding temperature was increased



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to 290 °C. The fracture mode of the solder joint at 290 °C was the brittle fracture mode with intergranular and transgranular fracture surfaces. Zhong [15] proved that the continuous $(Cu_{0.95}, Ni_{0.05})_6Sn_5$ IMC formed on the Cu interface, while $(Cu_{0.76}, Ni_{0.24})_6Sn_5$ IMC formed on the Ni interface. The interfacial IMCs at the cold end grew remarkably faster than that at the hot end under thermal migration, and the IMC growth rate on the Cu substrate was larger than that on the Ni substrate under the same conditions. Ji [16] showed that the IMCs in the Cu/Sn–0.7Cu/Ni solder joint consisted of $(Cu, Ni)_6Sn_5$ and $Cu_3Sn$ after ultrasonic-assisted die bonding of 10 s, and the shear strength was about 80.7 MPa. Huang [17] investigated the interfacial reactions of Ni/SnAg/Cu solder joints during TLP soldering. They found that the IMCs growth rate on the Ni side was larger than that on the Cu side in the Cu/Ni joint by 40 µm thick solder, while the growth reversed with the solder thickness was decreased below 20 µm. Zhao [18] found that the $(Ni, Cu, Zn)_5Zn_{21}$ IMC was formed on the Ni interface at 250°C for 5 min, and the IMC on the Cu interface was $Cu_5Zn_8$. The IMC was transformed to $(Ni, Cu)_3(Sn, Zn)_4$ on the Ni interface with the bonding time is increased to 240 min, and which of that on the Cu side were $Cu_6(Sn, Zn)_5$ and (Cu, Ni)(Zn, Sn).

In recent years, indium (In) solder has become one of the indispensable solders in the modern electronic packaging field due to its low melting point, good fatigue resistance and conductivity, and it is expected to become a solder to replace Sn solder [19]. The required bonding temperature of the solder joint by using In solder is lower than that of the solder joint by using Sn solder, and the high re-melting IMC phases are formed in the In/Cu solder joint [20].

There was currently little research on the connection between Cu and Ni substrates by using In solder. Lin [21] investigated the interfacial reactions of Cu/In/Ni solder joints at 280°C. In solder was completely consumed in the solder joint after bonding of 1440 min, and the IMCs in the joint consisted of $Ni_3In_7$ and $Cu_{11}In_9$ phases. The $Cu_{11}In_9$ is divided into $Cu_{11}In_9$ (i) phase on the Cu interface and $Cu_{11}In_9$ (ii) phase with faceted rod-like morphology in the *in situ* reaction zone.

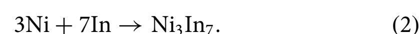
At present, the researches about the connection of the Cu/In–Cu/Ni composite solder joint were seldom reported. In the paper, the In–45Cu composite solder powders were prepared after adding about 45 wt% micron-sized Cu particles into the pure In solder powder, and then, the Cu/In–45Cu/Ni encapsulated solder joints were obtained by TLP bonding. The microstructure and the fracture morphologies of Cu/In–45Cu/Ni solder joints were observed. The shear strength of Cu/In–45Cu/Ni solder joints was tested. The IMCs growth mechanism of the Cu/In–45Cu/Ni solder joints was investigated.

## Results and Discussion

### Microstructure

Figure 1 shows the microstructure of Cu/In–45Cu/Ni solder joints at different bonding times. As shown in Fig. 1, the Cu/In–45Cu/Ni solder joints can be divided into three parts: interfacial diffusion reaction zone I on the Cu substrate, *in situ* reaction zone II and interfacial diffusion reaction zone III on the Ni substrate, and Cu particles basically no longer existed in the solder joint after bonding for 15–120 min. The numerous voids and residual In phase exist in the solder joint at 15 min [Fig. 1(a)]. Energy-dispersive spectroscopy (EDS) results show that the interfacial IMC at the Cu substrate is $Cu_{11}In_9$, the interfacial IMC at the Ni substrate is $Ni_3In_7$, and the IMC in the *in situ* reaction zone is $Cu_{11}In_9$. The same results are obtained by Lin [21], and the chemical reaction formulas are given as follows [22, 23]:

$$11Cu + 9In \rightarrow Cu_{11}In_9, \quad (1)$$



$$3Ni + 7In \rightarrow Ni_3In_7. \quad (2)$$

The voids and the residual In phase in the solder joints are decreased firstly and then increased with increasing bonding time. However, the IMCs in the *in situ* reaction zone are increased firstly and then decreased. As shown in Fig. 1(c), the Cu/In–45Cu/Ni solder joint is well connected when the bonding time is up to 60 min. The molten In particles continuously access the gap in the solder joint and react adequately with Cu particles to form In–Cu compounds after long bonding time. EDS results show that the interfacial IMC at the Cu substrate is transformed from $Cu_{11}In_9$ phase into $Cu_2In$ phase, and granule-like $Cu_2In$ phase appears in the *in situ* reaction zone [20]:

$$Cu_{11}In_9 + 7Cu = 9Cu_2In. \quad (3)$$

However, the continuous voids appear on the Ni side of the Cu/In–45Cu/Ni solder joint at 120 min. The Kirkendall effect is the reason of the voids formation [24, 25, 26]. More $Cu_2In$ phase is produced with longer bonding time, and the Kirkendall effect became more serious, as shown in Fig. 1(d). Tian [20] also finds that the Kirkendall effect is significant during the microstructure evolution of Cu/In/Cu joints, and Kirkendall voids occur along the Cu interface after bonding for 40 min. Other studies report this phenomenon in Cu/Sn/Cu systems, and the voids are usually located along the $Cu/Cu_3Sn$ interface [27, 28].

The average thickness of interfacial IMC in the diffusion reaction zone I and III is measured by ImageJ software, and its change trend can be clearly expressed. As shown in Fig. 2,

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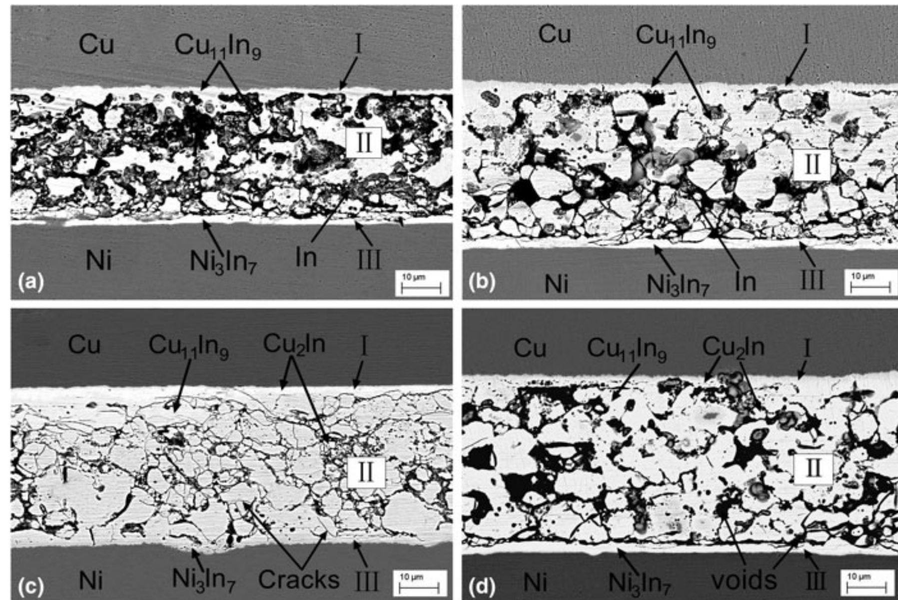


**Figure 1:** Microstructure of Cu/In–45Cu/Ni solder joints at different bonding times: (a) 15 min, (b) 30 min, (c) 60 min, and (d) 120 min.

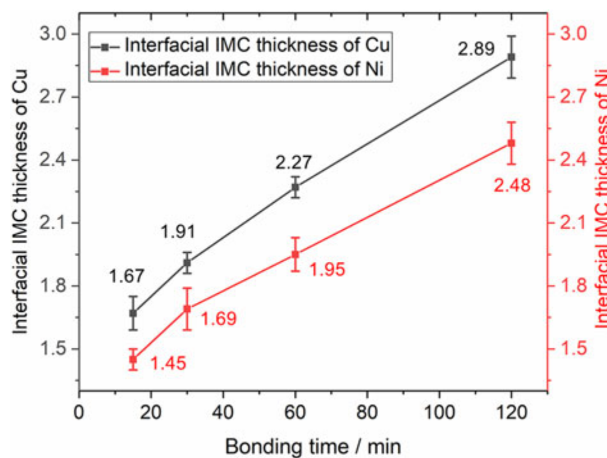


**Figure 2:** Relationship between interfacial IMC thickness and bonding time.

the interfacial IMC thickness of the Cu substrate and Ni substrate is about 1.67 and 1.45 μm at 15 min, respectively, and they are both increased with increasing bonding time. The IMC thickness in the diffusion reaction zone I of the Cu substrate interface is larger than IMC thickness in the diffusion reaction zone III of the Ni substrate interface at the same bonding time. It indicates that the diffusion rate of Cu atoms is greater than that of Ni atoms under the same bonding conditions. The EDS results of the Cu/In–45Cu/Ni solder joint at 120 min are shown in Fig. 3. As shown in Fig. 3(a), the number of Ni atoms is negligible in the *in situ* reaction zone. The same result is obtained by the EDS element mapping [Fig. 3(b)]. The similar results are obtained by Chen [29] and Rizvi [30]. Chen suggests that the diffusivity of Cu atoms in Sn solder is two orders of magnitude higher than that of Ni atoms, causing that Cu atoms would easily diffuse across the bulk solder than Ni atoms and influence the interfacial reactions. Rizvi considers that Cu atoms diffuse into the Sn–2.8Ag–0.5Cu–1.0Bi solder through the IMCs much faster than that of Ni atoms.

The IMCs volume ratio of Cu/In–45Cu/Ni solder joints at different bonding times is shown in Fig. 4. As shown in Fig. 4, the IMCs volume ratio is increased firstly and then decreased with increasing bonding time, and the maximum IMCs volume ratio is obtained at 60 min, which is 95.8%. Combining with Fig. 1(c), a small amount of cracks occur in the *in situ* reaction zone of the solder joint at 60 min, and it is caused by the volume contraction after the IMCs transformation.

The crystal structure is obtained by materials studio software. $Cu_{11}In_9$ phase is C2/m oblique crystal structure [31], and $Cu_2In$ phase is P63/mmc hexagonal structure. The lattice constants of $Cu_{11}In_9$ phase are $a = 13.027$ nm, $b = 4.406$ nm, $c = 7.460$ nm, and $\beta = 54.22°$. The lattice constants of $Cu_2In$ phase are $a = b = 4.471$ nm and $c = 5.384$ nm. The density of $Cu_{11}In_9$ and $Cu_2In$ is given as follows:

$$\rho_{Cu_{11}In_9} = \frac{11M_{Cu} + 9M_{In}}{N_A abc \sin\beta} = 8.28\ \mathrm{g/cm^3}, \quad (4)$$

$$\rho_{Cu_2In} = \frac{4M_{Cu} + 2M_{In}}{N_A abc} = 7.46\ \mathrm{g/cm^3}, \quad (5)$$

where $\rho_{Cu_{11}In_9}$ is the density of $Cu_{11}In_9$ phase; $M_{Cu}$, $M_{In}$ are the molar mass of Cu and In, respectively; $N_A$ is the Avogadro constant. The density of Cu and In is 8.92 and 7.31 g/cm$^3$, respectively, and then, the volume change of 11 mol Cu and 9 mol In after reacting and completely transforming to 1 mol



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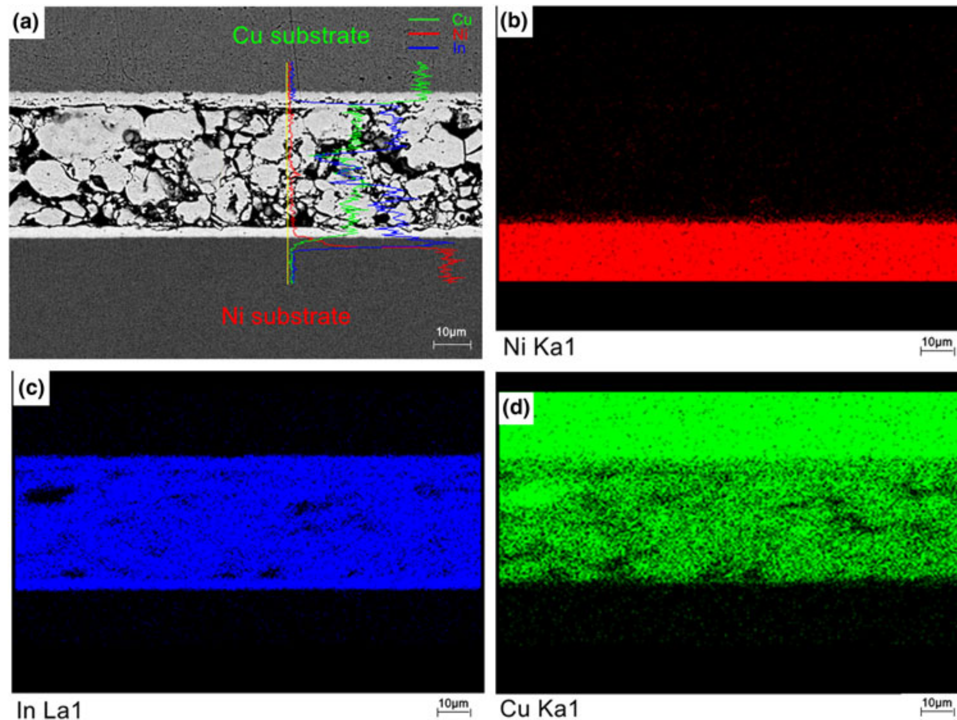


**Figure 3:** EDS results of the Cu/In–45Cu/Ni solder joint at 120 min (a) line-scanning and (b–d) Ni, In, and Cu elemental mapping images.

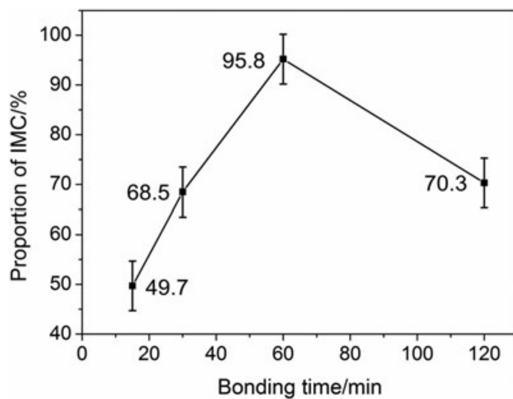


**Figure 4:** IMCs volume ratio of Cu/In–45Cu/Ni solder joints at different bonding times.

$Cu_{11}In_9$ can be expressed as follows:

$$\Delta V = \frac{11M_{Cu} + 9M_{In}}{\rho_{Cu_{11}In_9}} - \frac{11M_{Cu}}{\rho_{Cu}} - \frac{9M_{In}}{\rho_{In}} = -10.5\,\text{cm}^3. \quad (6)$$

Then, the volume shrinkage rate is obtained:

$$K = \frac{\Delta V}{11V_{In} + 9V_{Cu}} = \frac{-10.5}{78.3 + 141.3} = -4.8\%. \quad (7)$$

Similarly, the volume change is 32.75 $cm^3$, and the volume expansion rate is 12.65% after 1 mol $Cu_{11}In_9$ and 7 mol Cu being converted into 9 mol $Cu_2In$. The solder joint is composed of a large amount of $Cu_{11}In_9$ phase and a small amount of $Cu_2In$ phase at 60 min, and thus, the volume change is mainly manifested in volume shrinkage, which inevitably leads to a small amount of cracks in the *in situ* reaction zone. The volume shrinkage also appears in the Cu/Sn system. Sun [32] and Pan [33] find that the volume shrinkage is about 4.38 and 4.4% after the reaction of $Cu_6Sn_5$ transforms to $Cu_3Sn$, respectively.

The IMCs volume ratio is decreased to 70% when the bonding time is increased to 120 min, combining with Fig. 1 (d), the voids and cracks exist in the solder joint at 120 min. In summary, the Cu/In–45Cu/Ni solder joint with dense microstructure can be obtained by a bonding temperature of 260 °C, a bonding pressure of 5 MPa, and a bonding time of 60 min.

## Shear property

Figure 5 shows the effect of bonding time on the shear strength of Cu/In–45Cu/Ni solder joints. As shown in Fig. 5, the shear strength is increased firstly and then decreased with increasing bonding time. The shear strength of the solder joint is 12.53 MPa at 15 min, and the maximum value of 15.21 MPa is obtained at 60 min. Combining with Fig. 1, the dense microstructure of the solder joint is obtained at 60 min and IMCs volume ratio reaches the maximum value. Therefore, the joint is well connected, which effectively improves the bonding strength of the solder joint. Furthermore, the $Cu_2In$ phase is

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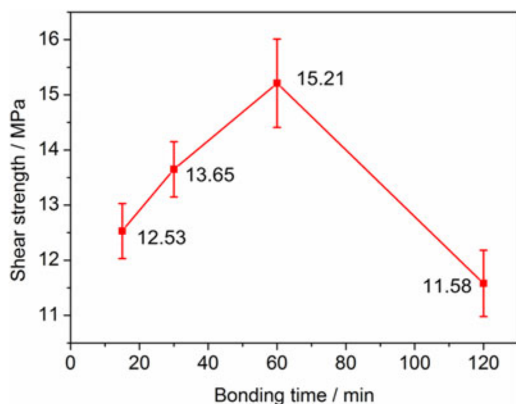


**Figure 5:** Shear strength of Cu/In–45Cu/Ni solder joints at different bonding times.

increased in the solder joint with the bonding time is increased to 60 min, and the $Cu_2In$ phase has better shear strength compared with $Cu_{11}In_9$ phase. The tensile strength of the solder joint consisting entirely of $Cu_{11}In_9$ IMC is 5.08 MPa, and that of the solder joint consisting entirely of $Cu_2In$ IMC is 13.65 MPa. In addition, the fractures of solder joints both occur in the IMCs phases. Therefore, the tensile strength of $Cu_2In$ phase is greater than that of $Cu_{11}In_9$ phase [20]. According to the Cu–In phase diagram, the melting points of $Cu_{11}In_9$ and $Cu_2In$ phases are 307 and 631 °C. As the melting point of $Cu_2In$ was much higher than that of $Cu_{11}In_9$, the $Cu_2In$ phase is more stable thermally and more suitable to improve the mechanical properties of Cu/In–45/Ni interconnections [20]. The shear strength of the solder joint is decreased to the minimum value of 11.58 MPa when the bonding time is 120 min. The continuous voids occur at the interface of substrate/IMCs [Fig. 1(d)], which greatly reduces the bond strength of the solder joint, resulting that the shear strength of the solder joint is significantly decreased.

In summary, the superior shear strength of the Cu/In–45Cu/Ni solder joint is obtained after bonding for 60 min, which is 15.21 MPa. Similar results are obtained by other researches. Tian [20] finds that the maximum shear strength of the Cu/In/Cu solder joint is 13.65 MPa, and the maximum shear strength 15.21 MPa obtained by our experiment is 11.43% greater than this value. Lee [34] considers the maximum shear strength of the Cu/In/Cu solder joint is 16.8 MPa.

Figure 6 shows the fracture morphologies of Cu/In–45Cu/Ni solder joints at different bonding times. The fracture shows a large amount of In particles and a small amount of $Cu_{11}In_9$ IMC at 15 min [Fig. 6(a)]. Combining with Fig. 1(a), the Cu/In–45Cu/Ni solder joint consists of a large amount of residual In particles and $Cu_{11}In_9$ phase the *in situ* reaction zone. It is prone to fracture during the shearing process due to the bad connection of the solder joint. The amount of In particles is decreased in the fracture with increasing bonding time, and the proportion of IMCs is increased. At 60 min, the fracture surface of the solder joint shows the IMCs morphology. EDS results show that IMCs are $Ni_3In_7$ and $Cu_{11}In_9$ phases, and the intergranular brittle fracture occurs at the interface of $Cu_{11}In_9/Ni_3In_7$ near the Ni substrate. The magnification of region A in Fig. 6(c) is shown in Fig. 6(d), and the fracture surface shows a uniform honeycomb-like structure.

The shear fracture process of the Cu/In–45Cu/Ni solder joint at 60 min is shown in Fig. 7, and the solder joint fractures at the interface of cylindrical $Cu_{11}In_9$ and $Ni_3In_7$ phases under the shear stress. After the separation of cylindrical $Cu_{11}In_9$ IMC and $Ni_3In_7$ IMC on the Ni substrate, a honeycomb-like structure appears in the fracture of the Ni substrate. The cracks at the phase boundaries of IMCs have a significant influence on the fracture mode of the solder joint [35, 36, 37]. According to the principle of minimum energy, the cracks propagation direction follows the path of least resistance, and thus, it is determined by the relationship between the grain boundaries strength and the strength of grain interior [38, 39]. The intragrain strength of IMCs gains is greater than the grain boundaries strength; therefore, the cracks initiate firstly in the voids and propagate along the grains boundaries when the solder joint is subjected to a shear deformation, resulting in the fracture of the solder joint [40, 41]. A number of voids exist at the interface of $Cu_{11}In_9$ and $Ni_3In_7$ phases boundaries, and the strength of the phase interior is greater than that of the phase boundaries. Therefore, the Cu/In–45Cu/Ni solder joint at 60 min is liable to fracture at the interface of $Cu_{11}In_9/Ni_3In_7$ phases on the Ni substrate under the shear stress.

The fracture surface shows granular IMCs morphology when the bonding time is increased to 120 min [Fig. 6(d)], and the IMCs are divided into cylindrical $Cu_{11}In_9$ phase and small granular $Cu_2In$ phase from EDS results. After long-time bonding, the cracks along the interface of $Cu_{11}In_9$ and $Cu_2In$ phases are increased due to the volume shrinkage, and thus, the shear fracture is likely to occur $Cu_{11}In_9/Cu_2In$ interface.

## IMCs growth mechanism

The microstructure of Cu/In–45Cu/Ni solder joints at 0.5–20 min is shown in Fig. 8. As shown in Fig. 8, the *in situ* reaction zone of the solder joints with the sandwich structure consists of In-rich phase, Cu particles, and Cu@IMC, and the thin interfacial IMCs exist at Cu and Ni substrates. EDS results show that the Cu@IMC in the *in situ* reaction zone and the interfacial IMC on the Cu substrate both are $Cu_{11}In_9$, and the interfacial IMC on the Ni substrate is $Ni_3In_7$.

As shown in Fig. 8, the residual In-rich phase and Cu particles in the *in situ* reaction zone are decreased gradually with increasing bonding time, and the thickness of the Cu@IMC is increased. The thickness of $Cu_{11}In_9$ and $Ni_3In_7$ interfacial IMC



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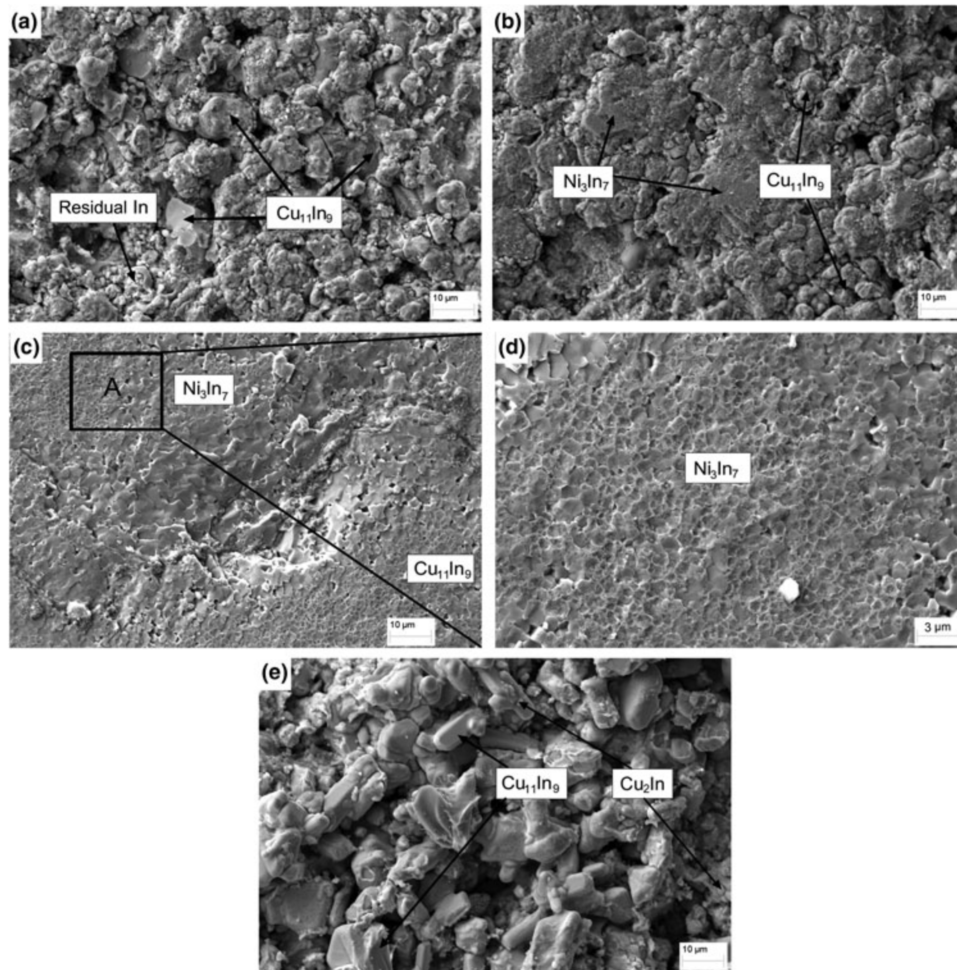


**Figure 6:** Fracture morphologies of Cu/In–45Cu/Ni solder joints at different bonding times: (a) 15 min, (b) 30 min, (c and d) 60 min, and (e) 120 min.

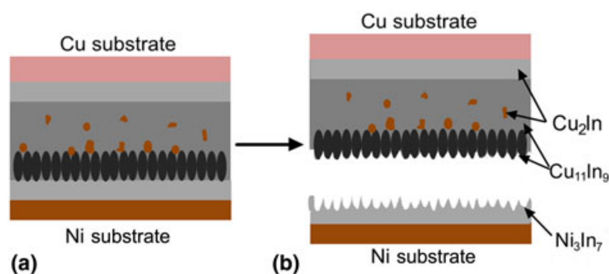


**Figure 7:** Shear fracture process of the Cu/In–45Cu/Ni solder joint at 60 min: (a) before shearing and (b) after shearing.

layer is both increased with increasing bonding time, and the interfacial IMCs layers are connected with the IMCs of the *in situ* reaction zone when bonding time is increased to 20 min.

As shown in Figs. 8(a) and 8(b), the thin $Cu_{11}In_9$ IMC is formed on the Cu particles surface at 0.5 min, which indicates that the nucleation and growth of $Cu_{11}In_9$ phase are very rapid during bonding. The bonding process is slow when In solder is used for bonding because the IMCs in the solder joint are only obtained by the reaction of In atoms and diffused Cu and Ni atoms from substrates. However, the In atoms can react quickly with the uniformly distributed Cu particles in the *in situ* reaction zone of solder joints using In–45Cu solder for bonding. In addition, the specific surface area of Cu atoms in the liquid In is increased after adding Cu particles, and the reaction between In and Cu atoms is promoted greatly. Therefore, the Cu@IMC is obtained quickly after bonding for 0.5 min.

Once the $Cu_{11}In_9$ phase is encapsulated, the subsequent growth of $Cu_{11}In_9$ depends mainly on the solid diffusion of Cu and In atoms, and then, the process is relatively slow. In and Cu atoms both follow the downhill diffusion mechanism, and the atomic diffusion channel at 20 min is longer than that at 0.5 min due to the increased IMCs thickness. The diffusion rate of In atoms at 20 min can be regarded as identical to that at 0.5 min, and thus, the reaction process of In and Cu atoms at 20 min is retarded for the lengthened diffusion channel. Therefore, the growth rate of IMCs thickness is decreased with the increasing IMCs thickness.

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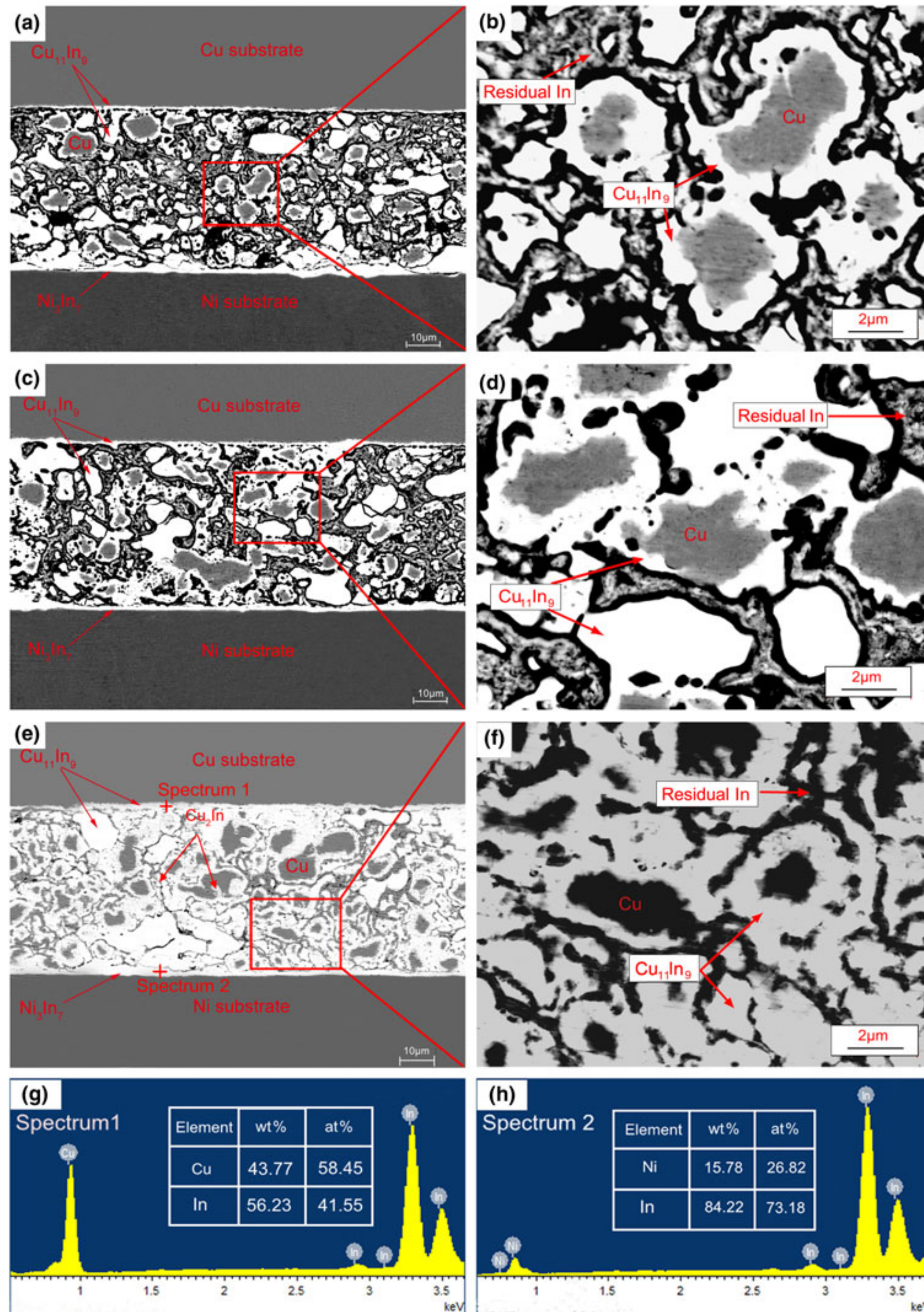


**Figure 8:** Microstructure of Cu/In–45Cu/Ni solder joints at different bonding times: (a and b) 0.5 min, (c and d) 5 min, (e and f) 20 min, (g) spectrum 1, and (h) spectrum 2.

In the *in situ* reaction zone, the IMCs nucleate and grow on the interface of Cu particles and liquid In phase. The excess In phase is gradually consumed with the increasing bonding time, and In–Cu IMCs and residual Cu particles are obtained finally after the bonding time of 20 min in the solder joint [Fig. 8(e)]. As shown in Fig. 8(e), a thin new phase appears between $Cu_{11}In_9$ phase and Cu particles, and EDS results show that it is $Cu_2In$. $Cu_{11}In_9$ phase is continuously converted to $Cu_2In$ phase by reacting with diffused Cu atoms, and $Cu_2In$ phase continues to grow along the $Cu_{11}In_9$/Cu interface with increasing bonding time [42].

Meanwhile, the island-shaped IMCs phase is found beside the Cu particles in the solder joint at 20 min. It may be formed by the reaction of the small Cu particles with In, and it may shed from the IMCs on the Cu particles surface. The amount of the IMCs in the *in situ* reaction zone is increased with

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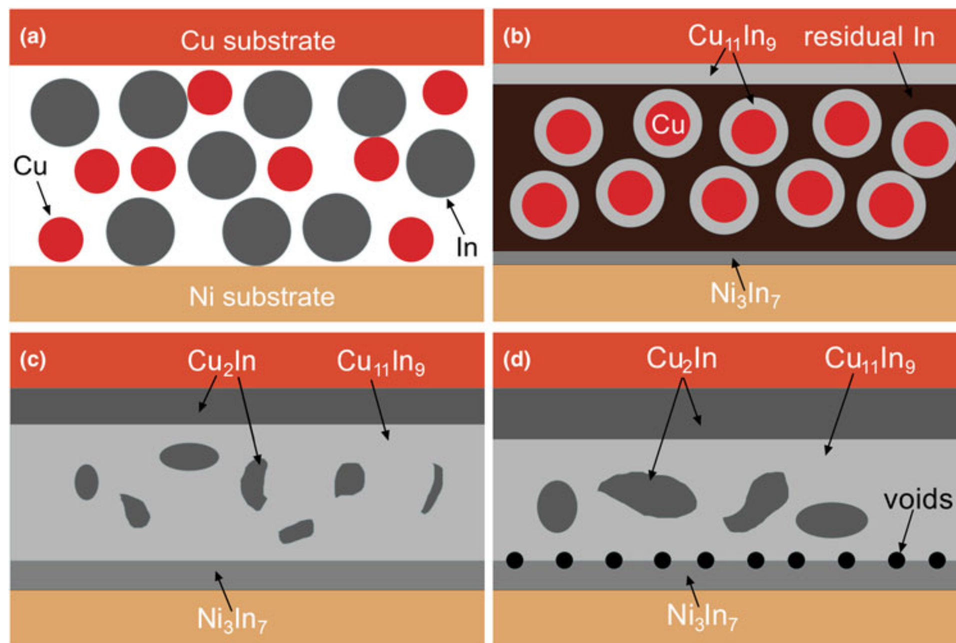


**Figure 9:** The schematic drawing of the microstructure evolution of Cu/In–45Cu/Ni solder joints at 260 °C for different times: (a) before bonding, (b) 0.5–20 min, (c) 60 min, and (d) 120 min.

increasing bonding time, to a certain extent, the IMCs contact with each other and combine with the growing IMCs on the substrates, and thus, the interconnection between Ni and Cu substrates is realized [as shown in Fig. 8(e)].

According to the Cu–In and Ni–In phases transformation of solder joints at different bonding times in Figs. 1 and 8, the schematic drawing of the microstructure evolution of Cu/In–45Cu/Ni solder joints formed at 260 °C is obtained (Fig. 9).

## Conclusions

In this study, Cu and Ni substrates were bonded by using In–45Cu composite solder paste. The microstructure and the mechanical property of Cu/In–45Cu/Ni solder joints were investigated under reflowed at 260 °C for 15–120 min. In addition, the IMCs growth mechanism was obtained after discussing the microstructure evolution between 0.5 and 120 min. According to the experimental results, the conclusions are summarized as follows:

(1) The IMCs volume ratio of Cu/In–45Cu/Ni solder joints is increased firstly and then decreased with increasing bonding time of 15–120 min, and the maximum IMCs volume ratio of the solder joint is 95.8% at 60 min. The interfacial IMCs Cu/In–45Cu/Ni solder joints with dense microstructure at 60 min are $Cu_2In$ and $Ni_3In_7$ phases, respectively, and the *in situ* reaction zone is composed of a large amount of $Cu_{11}In_9$ phase and a small amount of $Cu_2In$ phase.

(2) The shear strength of Cu/In–45Cu/Ni solder joints is increased firstly and then decreased with increasing bonding time, and the maximum value of 15.21 MPa is obtained at 60 min. The shear fracture mode is brittle intergranular fracture.

(3) The *in situ* reaction zone consists of unreacted In phase, Cu particles, and Cu@IMC in the solder joints at 0.5–20 min. The thickness of the interfacial IMCs and the Cu@IMC are both increased continuously with increasing bonding time, which ultimately realizes the interconnection of Cu–Ni substrates.

## Experimental

The In solder powder with a diameter of about 4–10 μm was used as the matrix, and about 45 wt% micron-sized Cu particles with a purity of 99.9% and a diameter of about 2–6 μm were added into In solder powder. In–45Cu composite solder powder was obtained after mixing In solder and Cu particles, and the morphology of In–45Cu powder was shown in Fig. 10(a). The Cu and In particles were evenly distributed in In–45Cu powder, and the size distribution of In and Cu particles was shown in Fig. 10(b). Then, about 11 wt% rosin flux was added in In–45Cu solder powder, and In–45Cu solder paste was obtained after long-time mechanical blending.

The size of the Cu substrate was 12 mm × 12 mm × 4 mm, and that of the Ni substrate was 10 mm × 10 mm × 4 mm. In–45Cu solder paste was evenly coated between Cu and Ni substrates, and the Cu/In–45Cu/Ni sandwich structure sample

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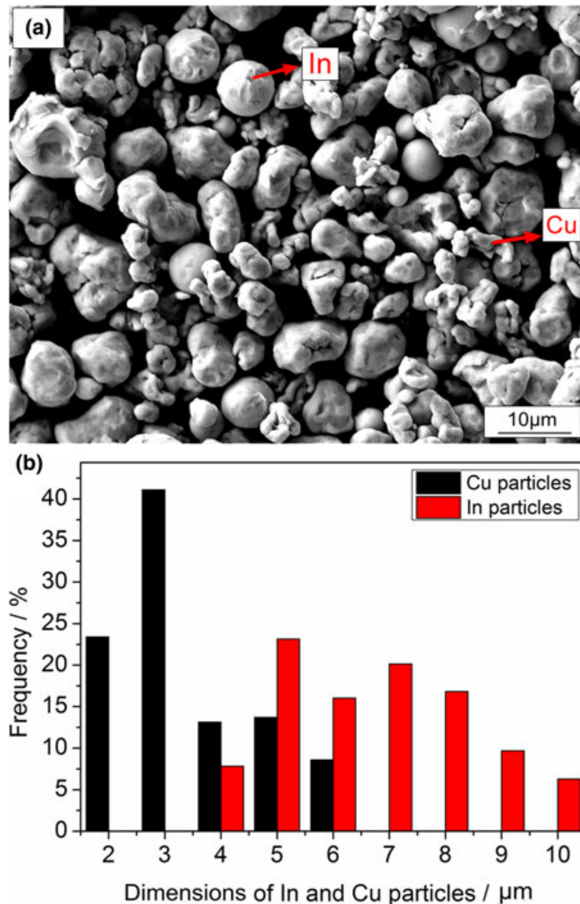


**Figure 10:** (a) Morphology of In–45Cu solder powder and (b) distribution of In and Cu particles dimensions.

was obtained. The sample preparation process and the experimental platform were shown in Supplementary Figure. The Cu/In–45Cu/Ni sample was placed in the TWB-100 wafer bonding machine under a vacuum of 1–5 Pa with a bonding temperature of 260 °C, a bonding pressure of 5 MPa, and a bonding time of 0.5–120 min. The Cu/In–45Cu/Ni solder joints were air-cooled to room temperature and washed by alcohol after bonding. The microstructure of the Cu/In–45Cu/Ni solder joint was observed by Zeiss supra 55 scanning electron microscope (SEM) equipped with EDS, and the phase composition of IMCs was analyzed by EDS. The IMCs volume ratio of the solder joints was measured by the ImageJ software.

The shear strength of the Cu/In–45Cu/Ni solder joint was tested by the UTMS 5305 metal material universal testing machine with a stretching rate of 0.02 mm/s. The average values of all data were taken after being tested for three times. The shear fractures of Cu/In–45Cu/Ni solder joints were observed by SEM.

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## Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1557/jmr.2020.194.

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