Investigation of Cu particles size and bonding time on the microstructure and shear property of Cu/In-45Cu/Cu solder joints

Li Yang\textsuperscript{1,4}, Gangang Wang\textsuperscript{2,4}, Yifeng Xiong\textsuperscript{3,4}\textsuperscript{*}, Sai Shen\textsuperscript{1} and Yaoceng Zhang\textsuperscript{3}

\textsuperscript{1} School of Mechanical Engineering, Guilin University of Aerospace Technology, Guangxi, 541004, People’s Republic of China
\textsuperscript{2} Suzhou Nuclear Power Research Institute, Institute of Welding Technology, Jiangsu, 215004, People’s Republic of China
\textsuperscript{3} School of Automatic Engineering, Changshu Institute of Technology, Jiangsu, 215500, People’s Republic of China
\textsuperscript{4} Authors to whom any correspondence should be addressed.

E-mail: linlidyu@126.com, gangangwang@163.com and 584098312@qq.com

Keywords: TLP bonding, Cu/In-45Cu/Cu solder joint, microstructure, shear property

Abstract

The effect of Cu particles size and bonding time on the microstructure and shear property of Cu/In-45Cu/Cu solder joint was studied, and the shedding mechanism of intermetallic compounds (IMCs) in the solder joint during transient liquid phase (TLP) bonding process was investigated. The results showed that the microstructure of Cu/In-45Cu/Cu solder joint was composed of Cu\textsubscript{11}In\textsubscript{9} phase, residual In phase and Cu particles, and the microstructure of solder joints prepared by small Cu particles was dense. The content of IMCs was increased with increasing bonding time, and the Cu/In-45Cu/Cu solder joint was composed of Cu\textsubscript{11}In\textsubscript{9} phase and Cu particles under bonding time 30 min. The Cu\textsubscript{13}In phase was formed in the solder joint at 60 min, and many cracks appeared at the interface of Cu\textsubscript{11}In\textsubscript{9} and Cu\textsubscript{2}In phases. The shear strength of Cu/In-45/Cu solder joints with brittle fracture was increased firstly and then decreased with increasing bonding time, and the maximum shear strength of the solder joint was 16.35 MPa at 30 min.

1. Introduction

With the rapid development of the third generation wide band gap semiconductor materials represented by SiC and GaN, the power devices with high-temperature resistance can be used up to 300 °C [1, 2]. The chips of core device, components and packages are laminated interconnection. The size of solder joints is decreased to 10 μm using 3D packaging technology, and the weight is reduced by 40–50 times [3]. The 3D components operate with a fast conversion speed with low energy consumption, and the solder joints using TLP technology for high temperature operation can be achieved [4, 5].

The manufacturing difficulties and the reliability problems are generated with the decreasing of solder joint size. These problems are mainly focus on the IMCs in solder joints [6], and the brittle IMCs reduce strength of solder joints and produce Kirkendall voids [7]. The overgrowth of IMCs layer is effectively controlled by adding the appropriate alloying elements, such as Mn [8], Ni [9], Ce [10], Pr [11], Fe [12], Bi [13], Sb [14], In [15], Ag [16], Zn [17] and other nano-scale oxide particles [18, 19].

Lots of research was carried out on the microstructure and mechanical properties of Cu/solder/Cu solder joints, but the previous studies were mainly focused on Sn-based solders. In is widely used for its low melting point, good fatigue resistance and ductility, and In solder is considered as an excellent commercial solder in the field of modern electronic packaging [20]. Tajima [21] investigated the IMCs evolution in the Cu/In-Sn-Ag-Sb/Cu solder joint, the Ag\textsubscript{5}Sn was replaced by Ag\textsubscript{5}(Sn, In) after adding In, and Ag\textsubscript{5}(In, Sn) was formed by the reaction between In and Ag\textsubscript{5}(Sn, In) with increasing In content. Lin [22] indicated that Cu/In/Ni solder joints with dense microstructure consisted of Ni\textsubscript{3}In\textsubscript{7} and Cu\textsubscript{11}In\textsubscript{9} IMCs, and the Cu\textsubscript{11}In\textsubscript{9} phase divided into Cu\textsubscript{11}In\textsubscript{9} (i) phase at the interface of Cu substrate and Cu\textsubscript{11}In\textsubscript{9} (ii) phase with faceted rod-like morphology in the in situ reaction zone. Yoon [23] pointed out the IMCs in the Au/In/Au solder joints were gradually transformed from AuIn\textsubscript{2} into Au\textsubscript{5}In\textsubscript{3} phases with increasing bonding time, and the time for Au\textsubscript{5}In\textsubscript{3} formation was greatly reduced.
with increasing bonding pressure. Tian [24] suggested that the IMC in the Cu/In/Cu solder joint was Cu_{11}In_{9} after the bonding of 40 min, and Cu_{2}In phase and Kirkendall voids appeared at the interface of solder joint at 360 min. The shear strength of solder joint reached the maximum value of 13.65 MPa at 40 min and the fracture mode is brittle cleavage fracture.

The researches mainly focused on the IMCs evolution and the effect of reinforced particles on the mechanical properties of solder joints. However, the effect of Cu particles size and bonding time on the microstructure and shear property of Cu/In/Cu solder joints was seldom reported. In the paper, micron-sized Cu particles with different size were added into the low melting point In solder, and the In-45Cu composite solder powders were prepared after mixing. TLP bonding was used to fabricate the Cu/In-45Cu/Cu solder joints. The microstructure of Cu/In-45Cu/Cu solder joints was observed, and its shear strength and the fracture morphologies were studied.

2. Experimental

The In solder powders with diameter about 1 μm was used as the matrix, and about 45 wt% micron-sized Cu particles with purity of 99.9% and diameter about 1 μm and 45 μm were added into In solder. Three different kinds of Cu particles were prepared, in which the small Cu particles accounted for 0%, 50% and 100% of total Cu particles. The Cu particles and the In particles were mixed with mass ratio of 11:9, and three In-45Cu composite solder powders were obtained. About 11 wt% rosin flux was added in In-45Cu solder powders, and In-45Cu solder paste was obtained after long-time mechanical blending.

The Cu substrates with the size of 10 mm × 10 mm × 4 mm and 12 mm × 12 mm × 4 mm were used in the experiment, and the In-45Cu solder paste was placed between the Cu substrates. The schematic diagram of the solder joint preparation was shown in figure 1. The Cu/In-45Cu/Cu sample was placed in the TWB-100 wafer bonding machine with the bonding temperature of 260 °C, the bonding pressure of 5 MPa and the bonding time of 3–60 min. The microstructure of the solder joints was observed by ZEISS SUPRA 55 scanning electron microscope (SEM) with energy disperses spectroscopy (EDS), and the void fraction of the solder joints was measured by the ImageJ software. The shear strength was examined by UTMS 5305 electronic universal tester with the shear rate of 0.2 mm min^{-1}, and the schematic diagram of the shear test was shown in figure 2. The shear fracture morphologies of Cu/In-45Cu/Cu solder joints were observed by SEM.

3. Results and discussion

3.1. Microstructure of solder joints with different size Cu particles

The microstructure of Cu/In-45Cu/Cu solder joints with different size Cu particles is shown in figure 3. As shown in figure 3, the microstructure of the solder joint consists of the IMCs around Cu particles, residual In and Cu particles, and the amount of IMCs in solder joint is increased with increasing content of small Cu particles. According to the Cu-In phase diagram, the main compounds are Cu_{11}In_{9} and Cu_{2}In phases at 260 °C. The atomic percentages of In and Cu in the white IMCs are 44.02 at% and 55.98 at% according to EDS results (as shown in figure 3(d)), inferring that the compound is Cu_{11}In_{9} phase.

As shown in table 1, the voids fraction of Cu/In-45Cu/Cu solder joint using small Cu particles is fewer than that of the solder joints using large Cu particles and mixed particles, and it is 16.78%. Combining with figure 3, the microstructure of solder joint using small Cu particles is dense. The schematic illustration of the voids formation in solder joints is shown in figure 4. The gaps among the large Cu particles exist in the solder joints. There is not enough liquid In-rich phase to replenish the original gaps among large Cu particles during bonding process, resulting void formation in the original gaps. As shown in figure 4(b), Cu_{11}In_{9} phase is easily formed on the Cu particles surface due to the large specific surface area of small Cu particles, and the gaps among small Cu particles is constantly filled by Cu_{11}In_{9} phase during bonding process. Therefore, the number of voids in the solder joint using small Cu particles is few, and a large amount of Cu_{11}In_{9} phase is formed (as shown in figure 3(c)). Researches indicate that rapid formation of compounds can lead to poor solder wettability [25, 26].
The wettability of In solder deteriorates due to the excessively fast formation of Cu₁₁In₉ phase in the solder joint using small Cu particles, and the voids still exist in the solder joint. Therefore, the size of Cu particles affects the filling influence of liquid phase In in the Cu/In-45Cu/Cu solder joints, and the dense microstructure of Cu/In-45Cu/Cu solder joint using small Cu particles is obtained.

3.2. Microstructure of solder joint with different bonding time

The microstructure of Cu/In-45Cu/Cu solder joints using small Cu particles at the bonding time of 3–60 min is shown in figure 5. The microstructure of Cu/In-45Cu/Cu solder joint is composed of a small amount of Cu₁₁In₉ phase, In-rich phase, and unreacted Cu particles with the bonding time of 3 min (as shown in figures 5(a), (b)). A large amount of voids exist in the solder joint, because the In-rich phase and Cu particles in the solder joint can not fully react due to the short bonding time, and there are not enough Cu-In phases to fill the gaps of Cu particles in the solder joint. The amount of Cu₁₁In₉ phase around Cu particles is increased with increasing bonding time, and the proportion of In-rich and unreacted Cu particles is decreased. The solder joint with dense microstructure consists of Cu₁₁In₉ phase and Cu particles at 30 min, and In is consumed substantially (figures 5(g), (h)). The reaction of the In-rich phase and Cu particles is substantially complete in the solder joint due to the appropriate bonding time of 30 min, and Cu-In phases can fill the gaps of Cu particles, causing the dense microstructure with a few voids. In addition, the number of voids is reduced due to the expansion of the IMC phases [27]. The Cu₁₁In₉ phase is firstly generated when In reacts with Cu [28–30]:

\[ \text{Cu}_1 + 9\text{In} = \text{Cu}_{11}\text{In}_9 \]  

(1)

And, Cu₂In phase is gradually formed with the increasing time [31]:

\[ \text{Cu}_{11}\text{In}_9 + 7\text{Cu} = 9\text{Cu}_2\text{In} \]  

(2)

Cu₁₁In₉ phase is C2/m oblique crystal structure, and Cu₂In phase is P6₃/mmc hexagonal structure [32]. The lattice constants of Cu₁₁In₉ phase are \( a = 13.027 \text{nm}, b = 4.406 \text{nm}, c = 7.460 \text{nm}, \) and \( \beta = 54.22^\circ, \) and the lattice constants Cu₂In phase are \( a = b = 4.471 \text{nm} \) and \( c = 5.384 \text{nm}. \) The density of Cu₁₁In₉ and Cu₂In as the following:

\[ \rho_{\text{Cu}_{11}\text{In}_9} = \frac{11M_{\text{Cu}} + 9M_{\text{In}}}{N_A abc \sin \beta} = 8.28 \text{ g cm}^{-3} \]  

(3)

\[ \rho_{\text{Cu}_2\text{In}} = \frac{4M_{\text{Cu}} + 2M_{\text{In}}}{N_A abc} = 7.46 \text{ g cm}^{-3} \]  

(4)

Where \( \rho_{\text{Cu}_{11}\text{In}_9} \) is the density of Cu₁₁In₉ phase; \( M_{\text{Cu}}, M_{\text{In}} \) are the molar mass of Cu and In; \( N_A \) is Avogadro constant.

The volume change of Cu₁₁In₉ + 7Cu → 9Cu₂In during the phase transition was theoretically calculated. When 1 mol Cu₁₁In₉ reacts with 7 mol Cu to convert 9 mol Cu₂In, the volume change is as follows:

\[ \Delta V = 9V_{\text{Cu}_2\text{In}} - (V_{\text{Cu}_{11}\text{In}_9} + 7V_{\text{Cu}}) \]  

(5)
Where $\Delta V$ is the volume change after Cu$_{11}$In$_9$ is converted to Cu$_4$In; $V_{\text{Cu}_1\text{In}_9}$ and $V_{\text{Cu}}$ are the volume of Cu$_{11}$In$_9$ phase and Cu before the reaction, respectively; $V_{\text{Cu}_2\text{In}}$ is the volume of Cu$_2$In after the reaction.

Then, the volume change after the reaction is:

$$\Delta V = \frac{9M_{\text{Cu}} + 2M_{\text{In}}}{P_{\text{Cu}_1\text{In}_9}} - \frac{11M_{\text{Cu}} + 9M_{\text{In}}}{P_{\text{Cu}_2\text{In}}} - \frac{7M_{\text{In}}}{P_{\text{In}}} = 32.75 \text{ cm}^3 > 0$$

Therefore, the volume expands after the Cu$_{11}$In$_9$ phase changes to Cu$_4$In. When the width of Cu/In-45Cu/In solder joints is a constant, the number of voids is reduced due to the expansion of the IMC phases. As shown in figure 5, the amount of Cu$_4$In phase of the solder joint at 30 min is more than the solder joint at 3–10 min, therefore there is only a few of voids in the tightly organized solder joints at 30 min.

**Table 1.** The effect of Cu particles size on the voids fraction.

| Particles type | Large particles | Mixed particles | Small particles |
|---------------|-----------------|-----------------|-----------------|
| voids fraction /% | 23.83           | 20.63           | 16.78           |

**Figure 3.** Microstructure of Cu/In-45Cu/Cu solder joints with different size Cu particles (a) Cu/In-45Cu/Cu solder joint of large particles, (b) Cu/In-45Cu/Cu solder joint of size mixed particles, (c) Cu/In-45Cu/Cu solder joint of small particles, (d) Spectrum 1.
A thin IMC layer is formed between the Cu particles and the Cu\(_{11}\)In\(_9\) when the bonding time reaches to 60 min (as shown in figure 4(j)). The atomic percentages of In and Cu atoms are 32.39 at% and 67.61 at% according to the EDS results (as shown in figure 5(k)), and it is inferred that the thin IMC layer is Cu\(_2\)In. As shown in figure 4(j), some cracks in the solder joints at 60 min, and it is caused by the different thermal expansion coefficients of the Cu\(_{11}\)In\(_9\) and Cu\(_2\)In phases [33]. The voids fraction of the solder joints at different

Figure 4. Schematic diagram of voids formation in Cu/In-45Cu/Cu solder joint.

Figure 5. Effect of bonding time on microstructure of Cu/In-45Cu/Cu solder joint using small Cu particles (a), (b) 3 min, (c), (d) 5 min, (e), (f) 10 min, (g), (h) 30 min, (i), (j) 60 min, (k) Spectrum 1.
bonding time is shown in Table 2. As shown in Table 2, the void fraction is decreased firstly and then increased with increasing bonding time, and the minimum void fraction of 3.18% is obtained at 30 min. Therefore, the Cu/In-45Cu/In solder joint with dense microstructure and a small amount of voids can be obtained when the bonding time is 30 min.

Cu$_{11}$In$_9$ phase sheds from the surface of the substrate and Cu particles in the Cu/In-45Cu/In solder joint according to Figures 5(d) and (i). The schematic diagram of compression stress of IMCs on the surface of Cu particles is shown in Figure 6(a). The compressive stress $\sigma$ of IMCs is subjected to liquid In during the growth stage. The IMC sheds from the substrate are caused by the force of $\sigma \sin \theta$ along the centerline of the attached Cu particles [34]. The shedding of Cu$_{11}$In$_9$ on the Cu substrate requires more force (as shown in Figure 6(b)), and a small amount of Cu$_{11}$In$_9$ phase peels off near the Cu substrate.

Table 2. The effect of bonding time on the voids fraction.

| Time / min | 3    | 5    | 10   | 30   | 60   |
|------------|------|------|------|------|------|
| voids fraction / % | 24.14 | 15.23 | 7.56  | 3.18  | 6.84  |
Cu$_2$In phase is formed on the surface of Cu particles, which causes the thermodynamic non-equilibrium state of the initially formed Cu$_{11}$In$_9$ compound and Cu particles. Cu$_{11}$In$_9$ phase sheds from the surface of Cu particles, providing the growth space of the Cu$_2$In equilibrium phase [35, 36].

3.3. Shear property

Figure 7 reveals the relationship between shear strength of Cu/In-45Cu/Cu solder joints and different bonding time. As shown in figure 7, the shear strength of Cu/In-45Cu/Cu solder joints is increased firstly and then decreased with increasing bonding time. The shear strength of Cu/In-45Cu/Cu solder joint is 8.51 MPa at 3 min, and it is increased to the maximum shear strength 16.34 MPa at 30 min. Tian [24] has also obtained similar results, the shear strength of Cu/In/Cu solder joint at 360 °C for 40 min is about 13.65 MPa, and the maximum shear strength 16.34 MPa in our experiments is about 19.71% larger than the shear strength of Cu/In/Cu solder joint. The shear strength of solder joint is guaranteed by constitute phase and voids in the solder joint [37]. The number of the weak region by the residual In and voids in the dense solder joint is relatively low. The stress distribution in the solder joint is relatively uniform. Therefore, the solder joint at 30 min presents superior shear strength. The voids and the residual In/IMC interfaces provides the crack initiation and propagation under the shear stress, the stress concentration on the crack tip promote to the fracture of the solder joint simultaneously. The high content of voids and residual In accelerates the fracture progress (figures 5(a)–(c)) and then the solder joint exhibits the inferior shear strength.

The shear fracture morphologies of Cu/In-45Cu/Cu solder joints at different bonding time are shown in figure 8. As shown in figure 8(a), the residual In particles exist in the fracture, and the fracture position of solder joint with brittle fracture mode locates in the solder matrix. The proportion of Cu-In IMCs in the fracture is increased with increasing bonding time, but the proportion of the Cu particles and residual In is decreased. As shown in figures 8(d), (e), a large amounts of Cu-In IMCs and a small amounts of Cu particles exist in the fracture at 30–60 min, and the fracture occurs in the Cu$_{11}$In$_9$ and Cu$_2$In IMCs. The bonding ability of the solder
joint is improved by IMCs gains, but the cracks between Cu$_2$In and Cu$_{11}$In$_9$ IMCs are formed in the solder joint at 60 min (Figure 5(e)).

4. Conclusions

(1) The microstructure of Cu/In-45Cu/Cu solder joint obtained by different size Cu particles is composed of Cu$_{11}$In$_9$ phase, residual In and Cu particles, and the microstructure of solder joints prepared by small Cu particles is dense.

(2) The solder joint is composed of Cu$_{11}$In$_9$ phase and Cu particles at the bonding time of 30 min, and In-rich phase is consumed completely. Cu$_2$In phase appears in the solder joint at the bonding time of 60 min, and cracks form between Cu$_{11}$In$_9$ and Cu$_2$In phases.

(3) The compressive stress and the thermodynamic forces cause Cu$_{11}$In$_9$ phase to shed from Cu particles and Cu substrate surface during the bonding process. The growth space of Cu$_2$In phase is provided by the shedding Cu$_{11}$In$_9$ phase at the bonding time of 60 min.

(4) The shear strength of Cu/In-45/Cu solder joints with brittle fracture mode is increased firstly and then decreased with increasing bonding time, and the maximum shear strength 16.35 MPa of the solder joint is obtained at the bonding time of 30 min.
Acknowledgments

This research was financially supported by the National Natural Science Foundation of China [grant numbers 51865006], Natural Science Foundation of the Jiangsu Higher Education Institutions of China [grant numbers 19KJA430001, 18KJA460001].

ORCID iDs

Yifeng Xiong  https://orcid.org/0000-0002-2905-8893

References

[1] Wang D, Li D and Zhao M 2018 Multifunctional wearable smart device based on conductive reduced graphene oxide/polyester fabric Appl. Surf. Sci. 454 218–26
[2] Maleessa N M and Idris S R A 2019 Effect of different amount of silicon carbide on SAC solder-Cu joint performance by using microwave hybrid heating method IOP Conf. Series Materials Science and Engineering 689 012110
[3] Genau M, Mutuku F and Cotts E J 2017 Effect of processing variables on the mechanical reliability of copper pillar SnAg solder joints 2017 IEEE 67th Electronic Components and Technology Conf. (ECTC) (https://doi.org/10.1109/ECTC.2017.250)
[4] Hadibeyk S, Beidokhti B and Sajjadi S A 2018 Effect of bonding time and homogenization heat treatment on the microstructural and mechanical properties of the transient liquid phase bonded dissimilar GTO-111 / FSX-414 TLP superalloys J. Alloys Compd. 731 929–35
[5] Xiong M Y, Zhang L and Sun L 2019 Effect of CuZnAl particles addition on microstructure of Cu/Sn58Bi/Cu TLP bonding solder joints Vacuum 167 301–6
[6] Li K and Wang X 2017 Effect of pulse current on the microstructure evolution of Cu–Sn intermetallic compounds Mater. Sci. Technol. 33 1–5
[7] Yang D, Cai J and Wang Q 2015 IMC growth and shear strength of Sn–Ag–Cu–Co–P ball grid array solder joints under thermal cycling J. Mater. Sci., Mater. Electron. 26 962–9
[8] Tang Y, Luo S M and Huang W F 2017 Effects of Mn nanoparticles on tensile properties of low-Ag Sn–0.3Ag–0.7Cu–xMn solder alloys and joints Journal of Alloys & Compounds 719 365–75
[9] Wang Y, Wang G and Song K 2017 Effect of Ni addition on the wettability and microstructure of Sn2.5Ag0.7Cu0.1Bi solder alloy Mater. Des. 119 219–24
[10] Yang D, Cai J and Wang Q 2015 IMC growth and shear strength of Sn–Ag–Cu–Co–P ball grid array solder joints under thermal cycling J. Mater. Sci., Mater. Electron. 26 962–9
[11] Ye H, Xue S and Luo J 2013 Properties and interfacial microstructure of Sn–Zn–Ga solder joint with rare earth Pr addition Mater. Des. 46 816–823
[12] Bakhthiar A and Iswadi M F M J 2016 Impact toughness, hardness and shear strength of Fe and Bi added Sn–1Ag–0.5Cu lead-free solders Microelectron. Reliab. 63 224–30
[13] Liu Y, Sun F and Zhang H 2012 Solderability, IMC evolution, and shear strength of low-Ag Sn0.7Ag0.5Cu–BiNi/Cu solder joint J. Mater. Sci., Mater. Electron. 23 1705–10
[14] El Basaty A B, Deghdayi A M and Eid E A 2017 Influence of small addition of antimony (Sb) on thermal behavior, microstructural and tensile properties of Sn–0.9Zn–0.5AlPb-free solder alloy Materials Science and Engineering: A 701 245–53
[15] Fallahi H, Nurulakmal M S and Fallahi Arezodar A 2012 Effect of iron and indium on IMC formation and mechanical properties of lead-free solder Mater. Sci. Eng., A 533 22–31
[16] Hu F Q, Zhang Q K and Jiang J F 2017 Influences of Ag addition to Sn–58Bi solder on SnBi/Cu interfacial reaction Mater. Lett. 214 142–5
[17] Wang F, Zhou L and Wang X 2016 Microstructural evolution and joint strength of Sn–58Bi/Cu joints through minor Zn alloying substrate during isothermal aging. J. Alloys Compd. 688 659–68
[18] Zhao N, Deng J F and Zhong Y 2017 Abnormal Intermetallic Compound Evolution in Ni/Sn/Ni and Ni/Sn–9Zn/Ni Micro Solder Joints Under Thermomigration J. Electron. Mater. 46 1931–6
[19] Hammad A E and Ibrahim A A 2017 Enhancing the microstructure and tensile creep resistance of Sn–3.0Ag–0.5Cu solder alloy by reinforcing nano-sized ZnO particles Microelectron. Reliab. 75 187–194
[20] Kumar D S, Suzuki N and Khanna P P 2016 Study of the oxidation effects on isothermal solidification based high temperature stable Pt/In/Au and Pt/In/Au thick film interconnections on LTCC substrate AIP Conference Proceedings 1715 020010–1–020010–10
[21] Tajima S, Satoh T and Ishizaki T 2017 Behavior of eutectic Sn–Bi powder in Cu nanoparticle joints during the thermal treatment J. Mater. Sci., Mater. Electron. 28 8764–70
[22] Lin S K, Wang Y H and Kuo H C 2015 Strong coupling effects during Cu/In/Ni interfacial reactions at 280 °C Intermetallics 58 91–7
[23] Yoon J W and Lee B S 2018 Sequential interfacial reactions of Au/In/Au transient liquid phase–bonded joints for power electronics applications Thin Solid Films 660 618–24
[24] Tian Y H, Hang C J and Zhao X 2014 Phase transformation and fracture behavior of Cu/In/Cu joints formed by solid-liquid interdiffusion bonding J. Mater. Sci., Mater. Electron. 25 4170–8
[25] Rivzi M J, Chan Y C and Bailey C 2005 Wetting and reaction of Sn–2.8Ag–0.5Cu–1.0Bi solder with Cu and Ni substrates J. Electron. Mater. 34 1115–22
[26] Zhu X, Zhang Z and Men X 2010 Rapid formation of superhydrophobic surfaces with fast response wettability transition Acta Applied Materials & Interfaces 2 3636–41
[27] Chen Z, Kumar A and Mona M 2006 Effect of phosphorus content on Cu/Ni–P/Sn–3.5Ag solder joint strength after multiple reflows J. Electron. Mater. 35 2126–34
[28] Noor E E M, Sharif F M and Yew C K 2010 Wettability and strength of In–Bi–Sn lead-free solder alloy on copper substrate J. Alloys Compd. 507 0–296
[29] Yoshikawa K, Yoshida N and Umemura M 2017 Direct integration of the collisionless boltzmann equation in, six-dimensional phase space: self-gravitating systems J. Alloys Compd. 437 186–190
[30] Joanna W R and Pawe Z 2009 Formation and growth of intermetallic phases in diffusion soldered Cu/In–Bi/Cu interconnections J. Alloys Compd. 476 0–171
[31] Lee K, Kim K S and Suganuma K 2011 Influence of indium addition on electromigration behavior of solder joint J. Mater. Res. 26 2624–31
[32] Piao S and Lidin S 2008 A new compound in the Cu–In system—the synthesis and structure of Cu_{10}In_{7} Z. Anorg. Allg. Chem. 634 2589–93
[33] Wen Y, Zhao X and Zhuo C 2017 Reliability enhancement of Sn–1.0Ag–0.5Cu nano-composite solders by adding multiple sizes of TiO_{2} nanoparticles J. Alloys. Compd. 696 799–807
[34] Magnussen O M, Zitrler L and Gleich B 2001 In-situ atomic-scale studies of the mechanisms and dynamics of metal dissolution by high-speed STM Electrochim. Acta 46 3725–33
[35] Cahn J W 2000 Wetting and non-wetting near critical points in solids Physica A 279 195–202
[36] Straumal B B, Kogtenkova O A and Kolesnikova K I 2014 Reversible ‘Wetting’ of grain boundaries by the second solid phase in the Cu–In system JETP Lett. 100 535–9
[37] Yang L, Zhou S and Zhang Y 2019 Reinforcement of vanadium on the microstructure and properties of Sn–58Bi lead-free solder joints Mater. Res. Express 6 066301