Effect of Sb Addition in Sn-Ag-Cu Solder Balls on the Drop Test Reliability of BGA Packages with Electroless Nickel Immersion Gold (ENIG) Surface Finish

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Abstract

Recently, Sn–Ag–Cu solders have been widely used as lead-free candidates for the Ball-Grid-Array (BGA) interconnection in the microelectronic packaging industry. However, widely used Sn-Ag-Cu solders such as with 3.0~4.0 wt% Ag in microelectronics exhibit significantly poorer drop test reliability than SnPb solder due to the low ductility of Sn-Ag-Cu solder bulk. The brittle failure of solder joints occurs at intermetallic compound (IMC) layer after drop test. Because the brittle nature of IMC or defects around IMC transfers a stress to the interfaces as a result of the low ductility of solder bulk. For the improvement of the drop test reliability by solder alloys, the low ductility of solder bulk and the IMC control at the interface are needed. In this paper, the bulk property of solder alloys and interfacial reactions with ENIG of Sb-added Sn-Ag-Cu solder were studied and finally, drop test was performed. Low Ag solder such as Sn1.0Ag0.5Cu and Sn1.2Ag0.5Cu0.5Sb showed higher ductility than high Ag solder such as Sn3.0Ag0.5Cu. In the interfacial reaction, all of the solders had $(Cu,Ni)_6Sn_5$ IMCs and P-rich Ni layer, however, Sn1.2Ag0.5Cu0.5Sb solder showed the lowest P-rich Ni layer thickness, because less Ni participated in the formation of $(Cu,Ni)_6Sn_5$ IMCs. In the drop test, the longer lifetime was in order of Sn1.2Ag0.5Cu0.5Sb, Sn1.0Ag0.5Cu, and Sn3.0Ag0.5Cu. Sn1.2Ag0.5Cu0.5Sb solder showed the best drop test reliability compared with other two solders due to the thinnest P-rich Ni layer. The failures of all packages occurred along P-rich Ni layer which is the most brittle phase at the solder/ENIG interface.

1. Introduction

SAC solders with 3.0~4.0 wt% Ag are most common lead-free solders due to low melting temperature and superior cyclic fatigue properties. However, these solders exhibit significantly poor drop test reliability that is common in the reliability evaluation of handheld electronic devices like cellular phone, PDA, MP3 player and digital camera [1]- [3].

To enhance the drop test reliability of SAC solders with 3~4wt.% Ag content, the mechanical properties of bulk solder alloys or IMC growth can be changed by modifying the solder composition. It is reported that Ag content is controlled to modulate the mechanical property of SAC solder bulk and minor additives is added to control IMCs formation [4, 5].

However, the effects of mechanical properties of solder alloys and interfacial reactions on the drop test reliability have not been sufficiently understood.

In this study, the effect of Sb additive on the drop test reliability of BGA packages with ENIG surface finish was investigated. Sn3.0Ag0.5Cu and Sn1.0Ag0.5Cu solder balls were prepared to understand the effect of Ag content. To understand the effect of Sb additive, Sn1.2Ag0.5Cu0.5Sb solder was prepared. The ball shear test and micro-hardness test were carried out to measure the mechanical property of solder alloys.

2. Experimental

In this study, three types of SAC solder balls, Sn3.0Ag0.5Cu (Reference composition), Sn1.0Ag0.5Cu, and Sn1.2Ag0.5Cu0.5Sb were prepared.

Ball shear strength was measured using Dage 4000 ball shear tester under the shear speed of 200 μm/s and the shear height of 20 μm. Hardness was measured by micro Vickers hardness tester under the test load of 9.807 mN. Both two tests were conducted after 1 time reflow for mounting of solder balls on ENIG pads. Reflow profiles, as shown in Fig.1, had 235℃ peak temperature and 30 sec reflow time.

To observe interfacial reactions of solder/ENIG, test specimens were mounted in epoxy resin and then cross sectioned, followed by grinding and polishing with 0.25 μm diamond paste. They were etched with a solution containing 2-nitrophenol 35 g/L and NaOH 50 g/L for clear IMC observation. The interfaces were examined by scanning electron microscopy (SEM) and the compositions of IMCs were identified by electron dispersive spectroscopy (EDS).

The size of ball grid array (BGA) package substrate was 10 mm x 10 mm in size with 64 solder balls (0.4 mm in diameter) reflowed on ENIG surface finish at a 0.75 mm pitch (Fig. 2). The printed wiring board used in this study was 132 mm x 77 mm x 1.5 mm in size with five units surface mounted on organic solderability preservertive (OSP) surface finish (Fig. 3).

In our drop test, we used 1500G acceleration peak and 0.5 ms duration time according to the JEDEC method (JESD22-

B111) (Fig. 4) [6]. During the drop test, electrical resistance was measured using an in-situ data acquisition system to detect failures during drop testing. After failures, the samples were cross sectioned and polished with 0.25 μm diamond paste and the failure sites and morphologies of BGA bumps were characterized using SEM.

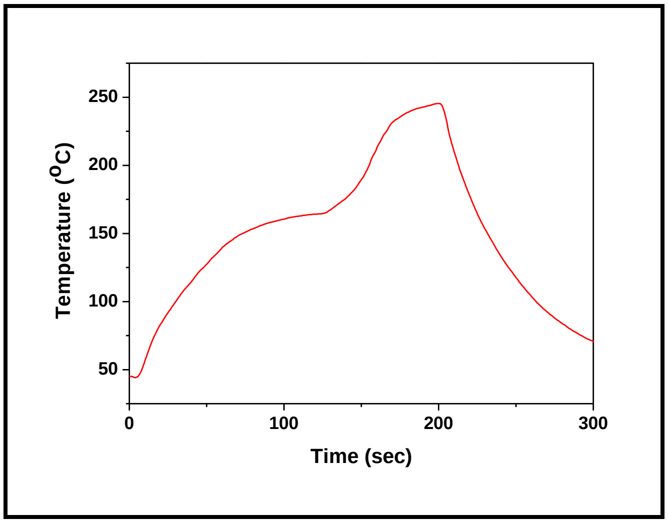

Fig. 1. Reflow profile of the Sn-Ag-Cu solders with ENIG metal finish.

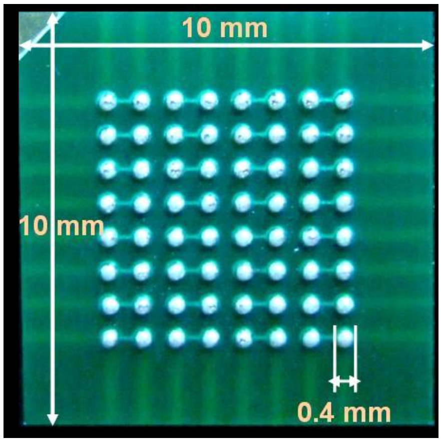

Fig. 2. BGA package substrate with 64 solder balls.

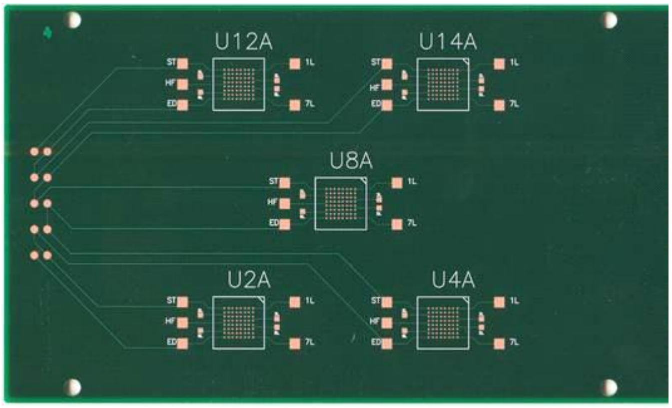

Fig. 3. JEDEC standard drop test board.

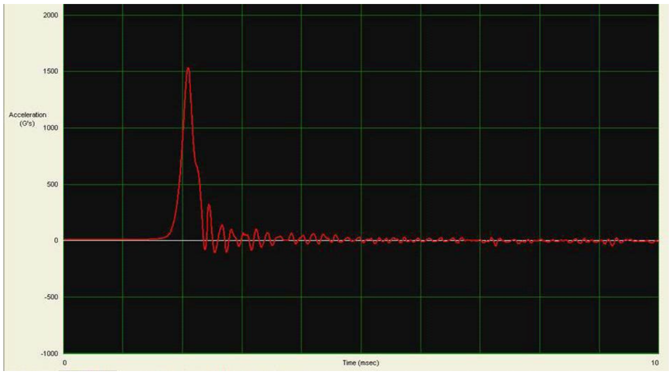

Fig. 4. Drop test profile of 1500G with 0.5ms

3. Result and Discussion

3.1. The mechanical properties of solder bulk

Figure 5 and 6 show ball shear strength and vickers hardness of three types of SAC solder balls. In the ball shear strength and micro-hardness test, the higher ball shear strength and vickers hardness was in order of Sn3.0Ag0.5Cu Sn1.2Ag0.5Cu0.5Sb, and Sn1.0Ag0.5Cu. As Ag contents increased, ball shear strength and Vickers hardness increased. The microstructures of each solder bulks are shown in Fig. 7. More fine Ag_3Sn IMCs were observed in Sn3.0Ag0.5Cu solder bulk than Sn1.0Ag0.5Cu solders due to more Ag content of solder. Solder bulk was reinforced by the precipitation hardening effect of Ag_3Sn IMCs in solder bulk.

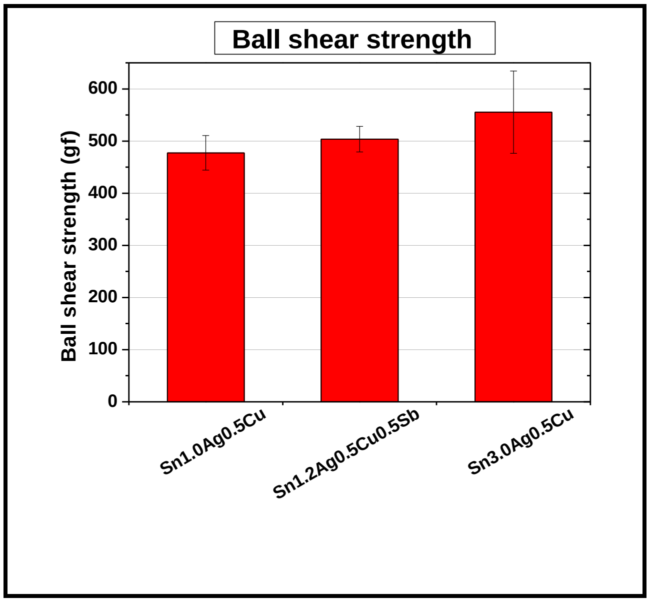

Fig. 5. The ball shear strength of three different solder balls with ENIG metal finish.

3.2. Interfacial reactions

Figure 8 and 9 shows the interface images between solder and ENIG after 1 time reflow. Sn1.0Ag0.5Cu and Sn3.0Ag0.5Cu solder had similar IMC morphologies. The IMCs of Sn1.0Ag0.5Cu and Sn3.0Ag0.5Cu were identified as $(Cu,Ni)_6Sn_5$ using EDS analysis. In the case of Sn1.2Ag0.5Cu0.5Sb, IMCs of irregular shape were formed and its composition was identified as $(Cu,Ni)_6Sn_5$. Thin dark layer was formed between all Cu-Ni-Sn IMCs and ENIG

(Fig. 10). The layer is called as P-rich Ni layer that was also formed as a by-product of Ni-Sn reaction between the Cu-Ni-Sn IMCs and ENIG due to phosphorus accumulated [7]. The P-rich Ni layers of three different solders were shown in Fig. 8. Sn1.0Ag0.5Cu and Sn3.0Ag0.5Cu solder showed almost same P-rich Ni layer thickness of 300~400 nm. On the other hand, Sn1.2Ag0.5Cu0.5Sb solder showed the lowest P-rich Ni layer thickness of about 100 nm. The EDS analyses of the $(Cu,Ni)_6Sn_5$ IMCs of Sn1.2Ag0.5Cu0.5Sb and Sn1.0Ag0.5Cu solder are shown in Fig. 11. and Table 1. In the case of Sn1.2Ag0.5Cu0.5Sb solder, less Ni from ENIG metal finish participated in the Cu-Ni-Sn IMCs formation. In other words, the formation of P-rich Ni layer was significantly reduced by Sb addition.

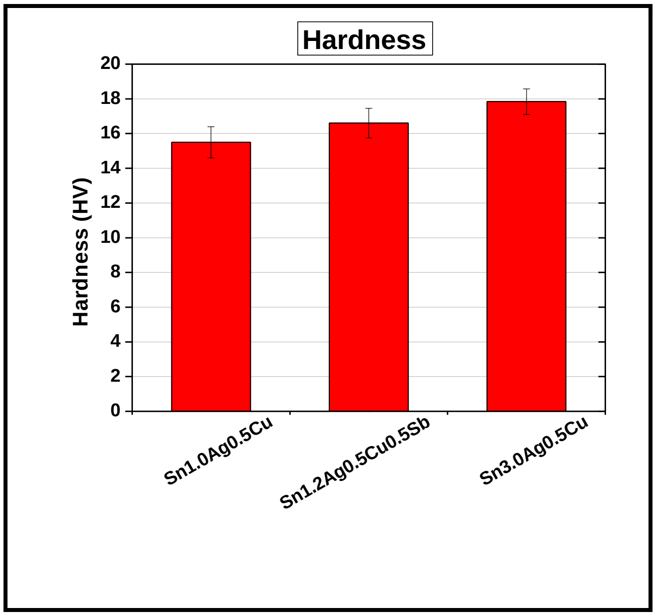

Fig. 6. The vickers hardness of three different solder ball with ENIG metal finish.

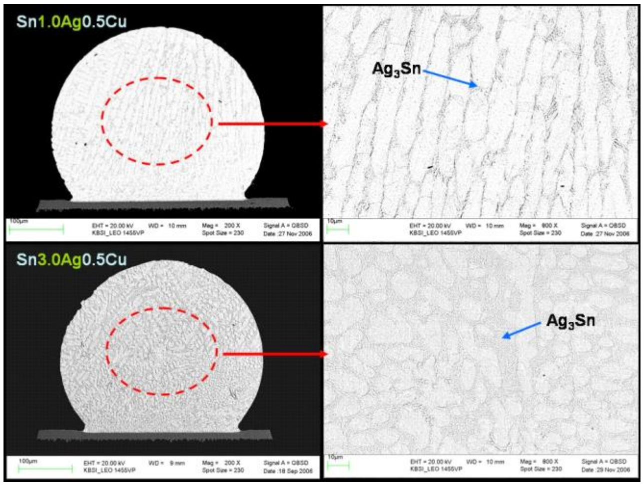

Fig. 7. The Ag_3Sn IMCs distribution of Sn1.0Ag0.5Cu and Sn3.0Ag0.5Cu in solder bulk.

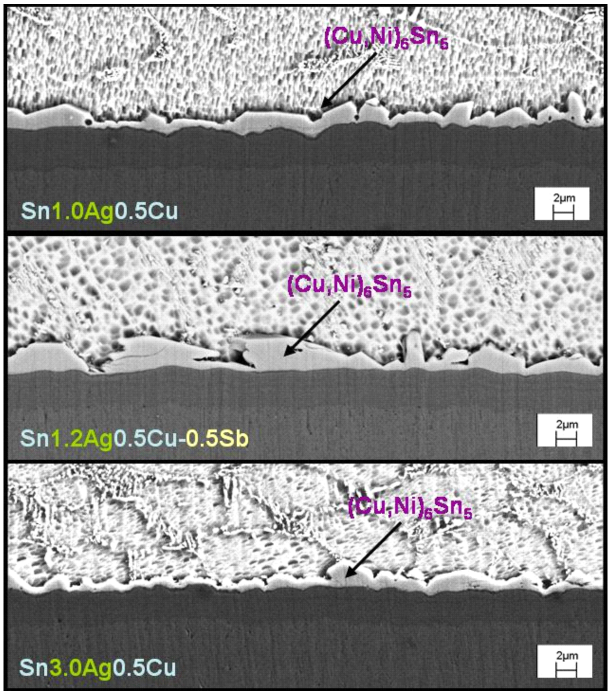

Fig. 8. The SEM images of three different solders/ENIG interface.

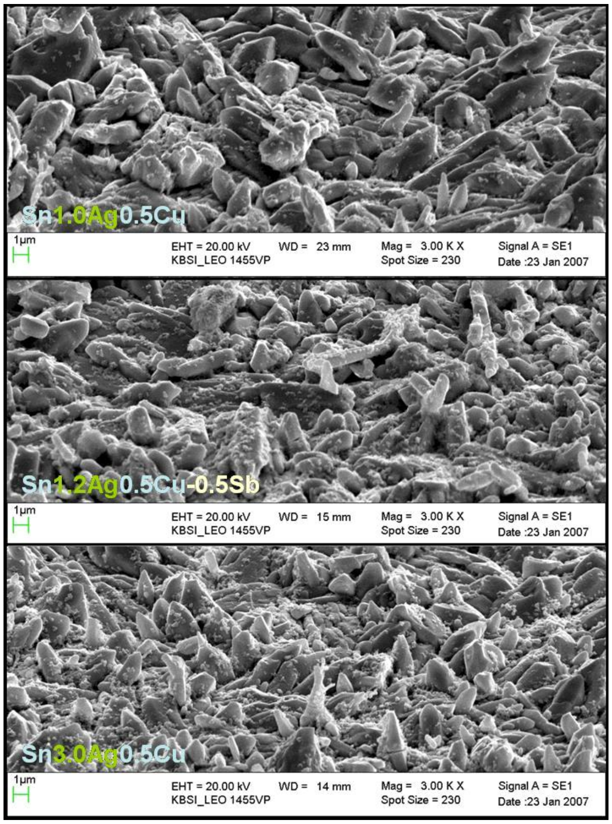

Fig. 9. Top view of $(Cu,Ni)_6Sn_5$ IMCs formed at three different solders/ENIG interface.

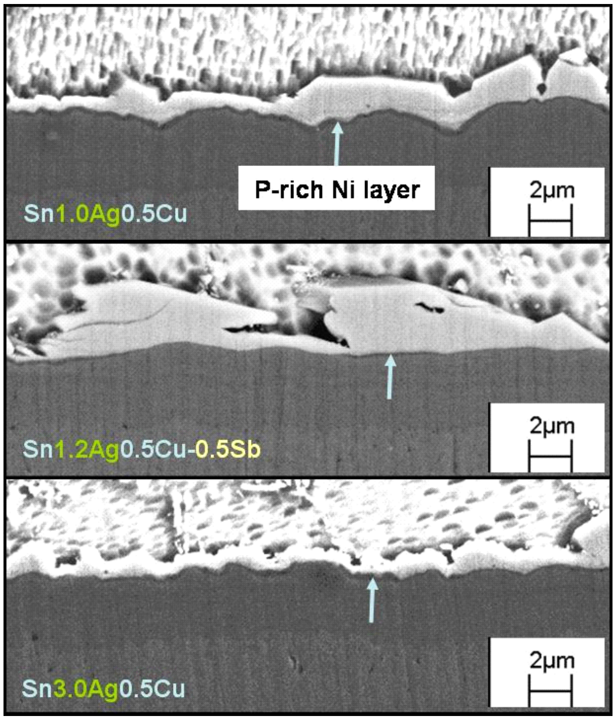

Fig. 10. P-rich Ni layer formed at the interface of $(Cu,Ni)_6Sn_5$ IMCs and ENIG.

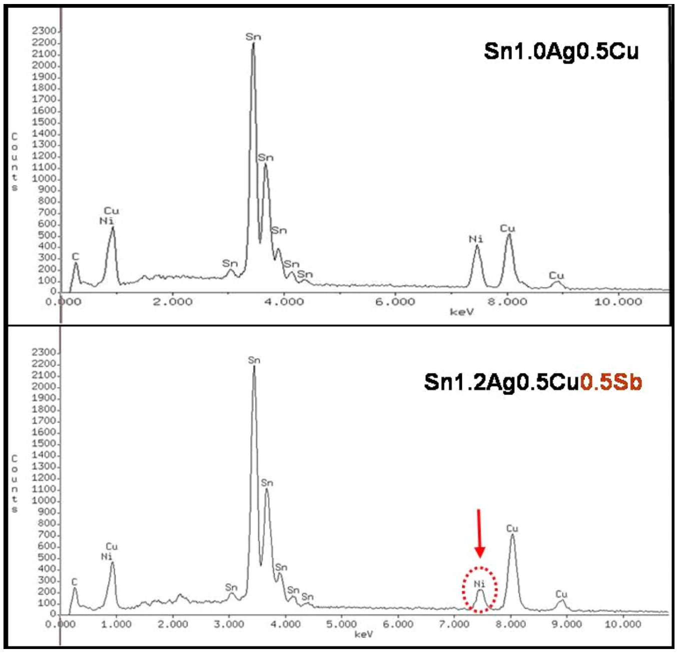

Fig. 11. The EDS analyses of the $(Cu,Ni)_6Sn_5$ IMCs of Sn1.0Ag0.5Cu and Sn1.2Ag0.5Cu0.5Sb.

Table 1. The $(Cu,Ni)_6Sn_5$ IMCs compositions of 3 different solders.

Solder	Cu (at.%)	Ni (at.%)	Sn (at.%)
Sn1.0Ag0.5Cu	30 ~ 35	17 ~ 23	44 ~ 48
Sn1.2Ag0.5Cu0.5Sb	37 ~ 45	7 ~ 15	44 ~ 48
Sn3.0Ag0.5Cu	30 ~ 35	17 ~ 23	44 ~ 48

3.3. Drop test

Figure 12 shows a weibull plot of the accumulated failure rate as a function of the number of drops. Sn1.2Ag0.5Cu0.5Sb solder showed significantly enhanced drop test reliability compared with other two solders. The number of drops of Sn1.0Ag0.5Cu until 66.7 % cumulative failure rate is 2 times higher than that of Sn3.0Ag0.5Cu. Because, low Ag solder (Sn1.0Ag0.5Cu) dissipates more energy during plastic deformation due to its ductile bulk property compared with high Ag solder (Sn3.0Ag0.5Cu).

In the case of Sn1.2Ag0.5Cu0.5Sb, the number of drops is 2 times higher than that of Sn1.0Ag0.5Cu. Failure sites of three types of solders were shown in Fig. 13. The failures of all packages occurred along P-rich Ni layer. Sn1.2Ag0.5Cu0.5Sb and Sn1.0Ag0.5Cu solder had similar ball shear strength, hardness and the failure site of drop test however, presented different P-rich Ni layer thickness. So the difference of drop performance between Sn1.2Ag0.5Cu0.5Sb and Sn1.0Ag0.5Cu solder is induced by Sb additive. P-rich Ni layer of Sn3.0Ag0.5Cu solder was similar to Sn1.0Ag0.5Cu however Sn3.0Ag0.5Cu solder showed poorer drop performance due to the difference of bulk property. As a result, the Sb addition in Sn-Ag-Cu solder balls enhanced the drop test reliability, because less Ni participated in Cu-Ni-Sn IMCs formation resulting in the lowest P-rich Ni layer thickness.

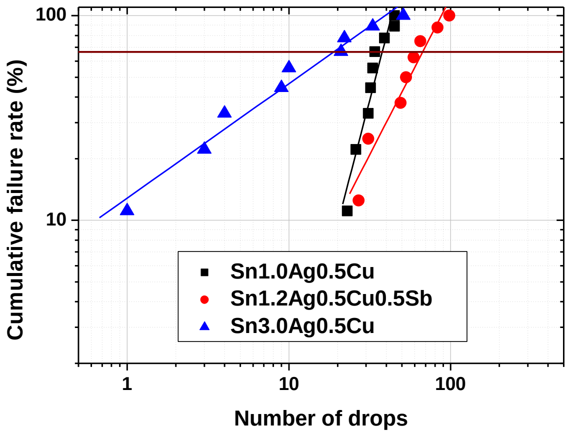

Fig. 12. Cumulative failure rate vs. the number of drops after drop testing of BGA packages with three different solders.

4. Conclusions

Lead free SAC solder with 0.5 wt% Sb addition shows significant improvement in drop test reliability on ENIG surface finish. Solder bulk properties show little difference between Sn1.2Ag0.5Cu0.5Sb and Sn1.0Ag0.5Cu, however, P-rich Ni layer thickness is reduced by Sb addition. In the case of Sn3.0Ag0.5Cu solder, P-rich Ni layer thickness is similar to Sn1.0Ag0.5Cu, however, drop test reliability is poorer due to high Ag content. Therefore, Adding a small amount of Sb attributes to enhance the drop test reliability on ENIG surface finish by the suppression of P-rich Ni layer growth. And lowering Ag content of SAC solder enhances the drop test reliability due to the ductile mechanical property of the solder bulk.

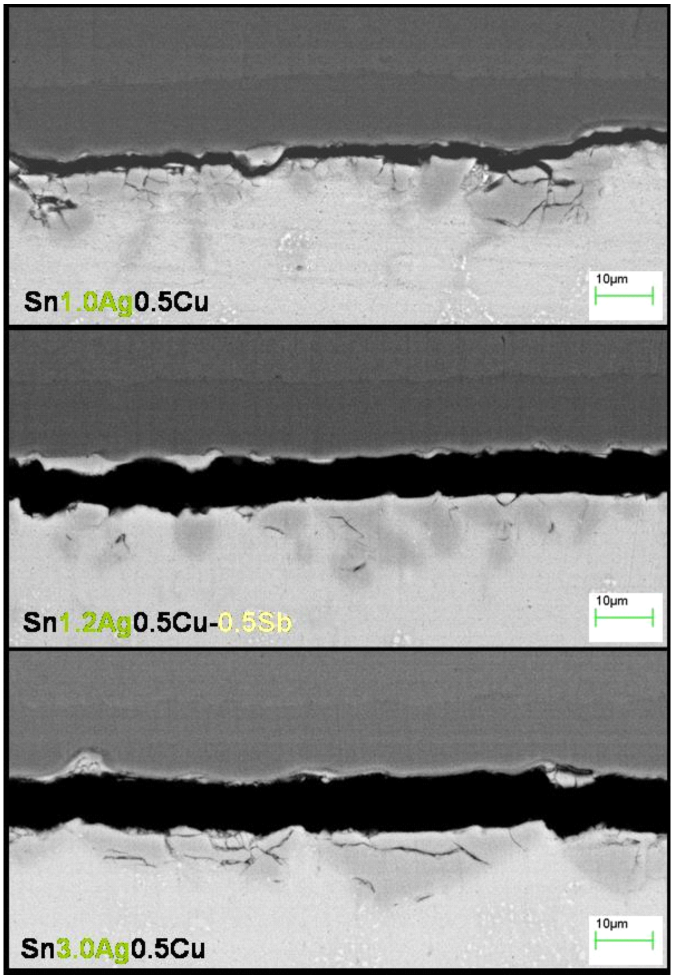

Fig. 13. The SEM images of the failure sites after drop testing of BGA packages with three different solders.

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