Presented at IPC Printed Circuits Expo®
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Designers Summit 04

Conquer Tombstoning in Lead-Free Soldering

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Abstract
Tombstoning of SnAgCu is affected by the solder composition. At vapor phase soldering, both wetting force and wetting time at a temperature well above the melting point have no correlation with the tombstoning behavior. Since tombstoning is caused by unbalanced wetting force, the results suggest that the tombstoning maybe dictated by the wetting at the onset of paste melting stage. A maximal tombstoning rate is observed at 95.5Sn3.5Ag1Cu. The tombstoning rate decreases with increasing deviation in Ag content from this composition. DSC study indicates that this is mainly due to the increasing presence of pasty phase in the solders, which is expected to result in a slower wetting speed at the onset of solder paste melting stage. Surface tension plays a minor role, with lower surface tension correlates with a higher tombstoning rate. SnAgCu composition with a Ag content lower than 3.5%, such as 2.5Ag, is more favorable in terms of reducing tombstoning rate with minimal risk of forming Ag_3Sn intermetallic platelet.

Key words: tombstoning, solder, soldering, solder paste, flux, lead-free, surface mount

Introduction
Tombstoning has been plaguing the surface mount assembly industry for decades. Although the situation appeared to be gradually under control with improved material, design, and process manipulation, particularly with the vapor phase reflowing technology fading out as one of the mainstream soldering technology, the problem is creeping back again with increasing presence of tiny discretes such as 0402 or 0201. Recent global move toward lead-free soldering augment the concern about tombstoning, presumably due to the speculated high surface tension of lead-free solders. In this study, tombstoning behavior was studied on a series of SnAgCu lead-free solders, with an attempt to identify a possible "composition window" for controlling this problem. Eutectic SnPb was included as the baseline. Properties may be related to tombstoning such as alloy surface tension, alloy melting pattern, and solder wetting behavior were also investigated in order to assess the critical characteristics required to harness this problem.

Experimental
Solder Materials
Five SnAgCu alloys were tested, including 97.5Sn2.0Ag0.5Cu, 96.7Sn2.5Ag0.8Cu, 96.5Sn3.0Ag0.5Cu, 95.5Sn3.5Ag1.0Cu, and 95.5Sn3.8Ag0.7Cu. Also tested was the control 63Sn37Pb. For each SnAgCu alloy, a solder paste composed of 89% of solder powder and a no-clean rosin-based flux was made. The same flux was also used for making SnPb solder paste with 90% metal content. All solder powder used in this study exhibits a particle size of 25-45 microns.

Experimental Procedure
Tombstoning Test
A 20 cm x 15.2 cm tombstoning board with Cu metallization was employed for tombstoning testing. In each test, 169 of 0402 chips were placed on each test board for each paste, with equal amount of parts being placed on the same board for another paste. To further reduce the possible performance difference due to printing, the pastes were printed alternately on these two pair of patterns.

A Manix vapor phase reflow oven was used for the tombstoning evaluation of the pastes. A Solvay Solexis HS-260 vapor phase reflow fluid with a boiling point of 260°C was used for the SnAgCu pastes, and a 3M Fluorinert 70 fluid with a boiling point of 215°C was used for SnPb paste. For each target paste, eight boards were reflowed. Altogether, there were 1352 chips soldered for each paste.

The reflow profiles for the SnAgCu alloys and SnPb alloy are shown in Figure 1 and Figure 2, respectively.

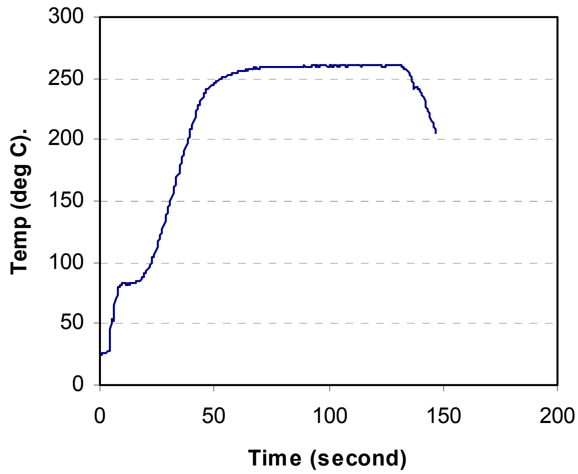

Figure 1 - The Reflow Profile for the SnAgCu Pastes using a Vapor Phase Fluid with a Boiling Point of 260°C

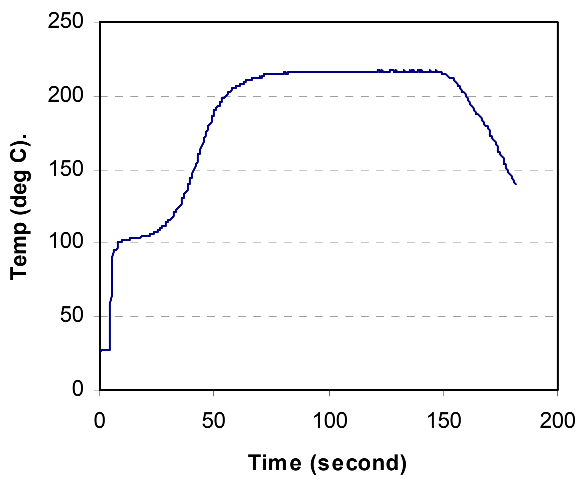

Figure 2 - The Reflow Profile for the 63Sn37Pb Paste using a Vapor Phase Fluid with a Boiling Point of 215°C

Wetting Force and Wetting Time of Liquid Solder
The wetting force and wetting time were also considered important in determining the tombstoning performance of a solder paste. In the present study, the aforementioned Multicore MUST wetting balance was employed to measure the wetting forces and wetting times of the solders on the Cu coupons using the same no clean flux that was used for manufacturing the solder pastes. The experimental procedure followed the IPC-TM-650 with corrected buoyancy. In this test, the dip speed was 2 cm/sec, the height was 2.5 cm, and the time limit was set at 4 seconds. The solder pot was maintained at 245°C for the SnPb alloy and 260°C for the SnAgCu alloys.

Differential Scanning Calorimetry (DSC)
It was well established that the melting behavior of the solder alloys had a significant impact on the tombstoning performance of the solder pastes. Modifications on the melting behaviors of solder alloys have been employed to reduce the tombstoning in electronics manufacturing.[1-5] Thus, it is very important to evaluate the melting of the target solder alloys using differential scanning calorimetry (DSC). In the present study, a SEIKO DSC5220 with a heating rate of 5°C/min and nitrogen purge was employed. Solder powder as received was used as specimen.

Surface Tension Test
The tombstoning performance of solder pastes has been speculated to be related to the surface tension of the respective solder alloys. In the present study, a Muticore MUST wetting balance was used to measure the surface tension of the solder alloys following the conditions established by Miyazki et al.[6] A piece of alumina coupon with a dimension of 2.5 cm x 0.4 cm x

0.062 cm was used for the testing. The solder pot was maintained at 245°C for the SnPb alloy and 260°C for the SnAgCu alloys. The dip speed was at 0.5 cm/sec, and the height at 2.5 cm. The measured force with respect to time was translated to a graph of force vs. dip depth based on the dip speed. When the alumina piece immersed into the solder for a certain depth where the meniscus became stable, the measured force was proportional to the displaced volume of solder. This force may be described as follows:

$$F = L \gamma + \rho g h A.$$

L was the circumference of the alumina piece. γ was the surface tension, ρ was the density of the solder alloy, and h was the dip depth and A was the cross-sectional area of the displaced volume. In this force vs. dip depth graph, as the h was extrapolated to zero, the $F = L \gamma$ and thus the surface tension γ was obtained. In the present work, the surface tension of the 63Sn37Pb was measured to be 0.51± 0.01 N/m, which was consistent with the value of 0.506 obtained by Miyazaki et al.[6]

Results

Tombstoning Test

The tombstoning test results are illustrated in Figure 3.

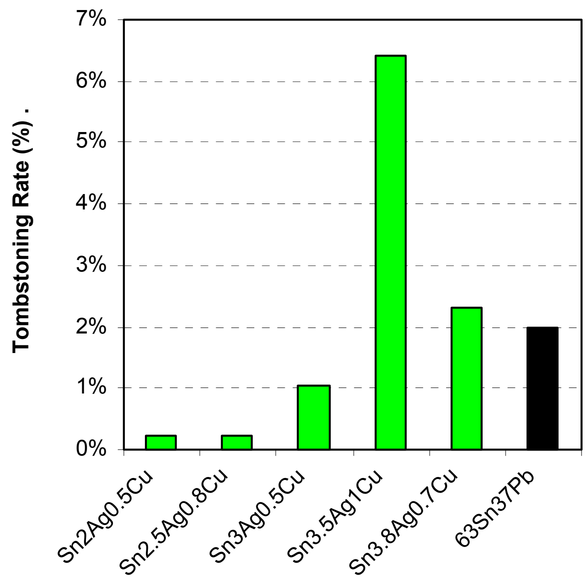

Figure 3 - Tombstoning Rate of Solder Pastes with Vapor Phase Reflow Process - Here SnAgCu and SnPb Pastes were Reflowed at 260°C and 215°C, Respectively

For Pb-free solders, the tombstoning rate is the highest for 95.5Sn3.5Ag1Cu, and appears to decrease with increasing deviation in Ag content from 3.5Ag. The defect rate of 63Sn37Pb is slightly lower than that of 95.5Sn3.8Ag0.7Cu. It is interesting to note that reflow temperature has negligible effect on tombstoning rate of 63Sn37Pb, as evidenced by the 2.00% and 2.24% tombstoning rate observed for 63Sn37Pb when reflowed at 215°C and 260°C, respectively.

Wetting Force and Wetting Time of Liquid Solder

The wetting force and wetting time of liquid solders are shown in Figure 4 and Figure 5, respectively. All SnAgCu solders exhibit a comparable wetting force which is considerably lower than that of 63Sn37Pb. No relation can be established between tombstoning rate and wetting force. Since wetting force is a function of wetting ability, surface tension, and temperature, this lack of correlation is attributable to the complicate effect of each parameter to the tombstoning.

On the other hand, the wetting time of SnAgCu system at 260°C seems to show some weak correlation with the tombstoning rate, with a longer wetting time correlating with a higher tombstoning rate. This relation is opposite to the earlier findings, where a faster wetting system typically results in a higher tombstoning rate.[7, 8] Since this possible new relation works against the physics law, it is accordingly stipulated that perhaps the tombstoning should be correlated with the wetting behavior at the incipient solder paste melting stage, instead of the wetting at a temperature well above the melting point. The relative wetting ability of various alloys may be significantly different for these two conditions, and the unbalanced wetting at the two ends of chip may already be developed at the onset of paste melting stage.

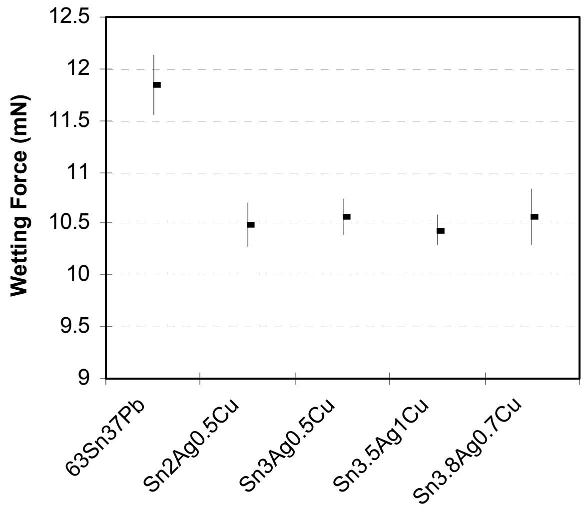

Figure 4 - Wetting Force of 63Sn37Pb and SnAgCu Solder Alloys determined at 245°C and 260°C, Respectively

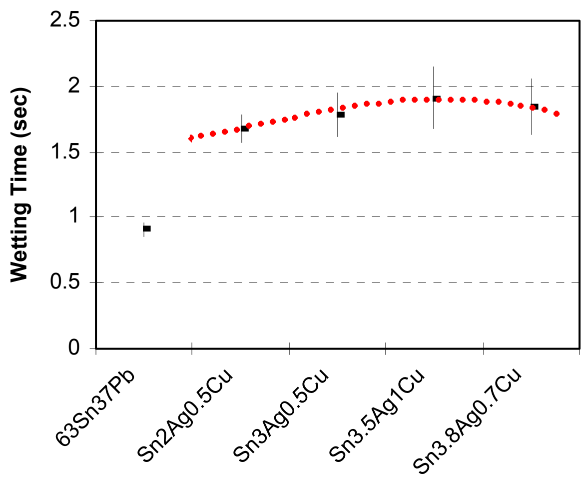

Figure 5 - Wetting Time of 63Sn37Pb and SnAgCu Solder Alloys determined at 245°C and 260°C, Respectively

DSC
The DSC melting curves of the powder of 63Sn37Pb and SnAgCu alloys are shown in Figure 6 to Figure 11:

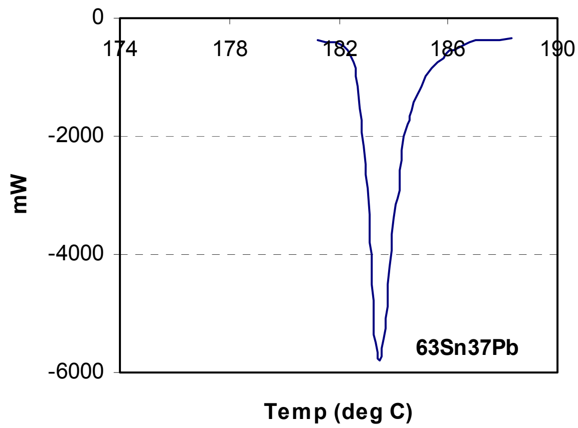

Figure 6 DSC Thermograph of 63Sn37Pb Alloys

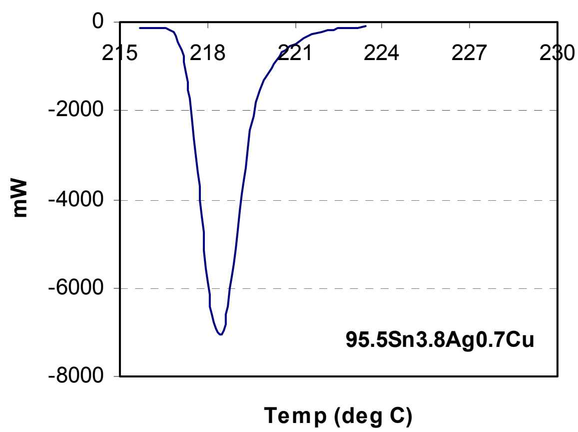

Figure 7 - DSC Thermograph of 95.5Sn3.8Ag0.7Cu

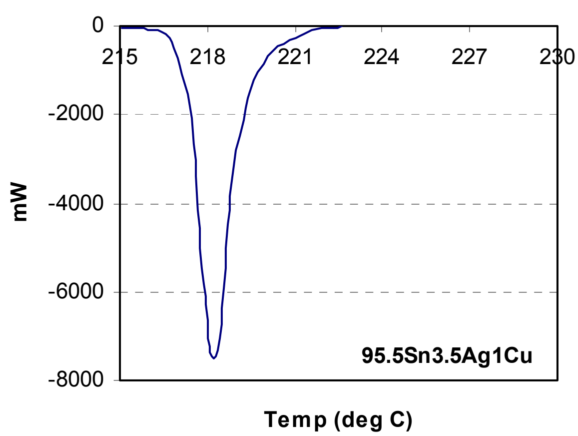

Figure 8 - DSC Thermograph of 95.5Sn3.5Ag1Cu.

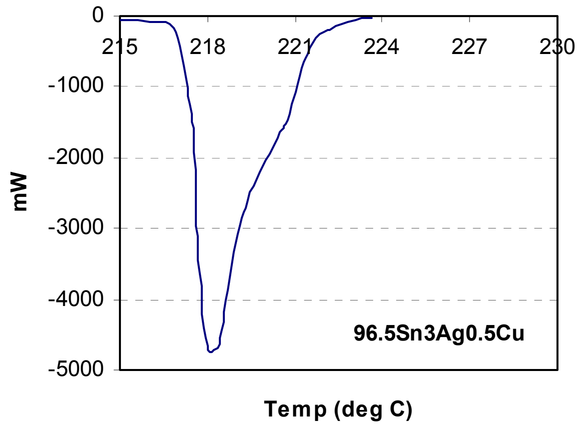

Figure 9 - DSC Thermograph of 96.5Sn3Ag0.5Cu

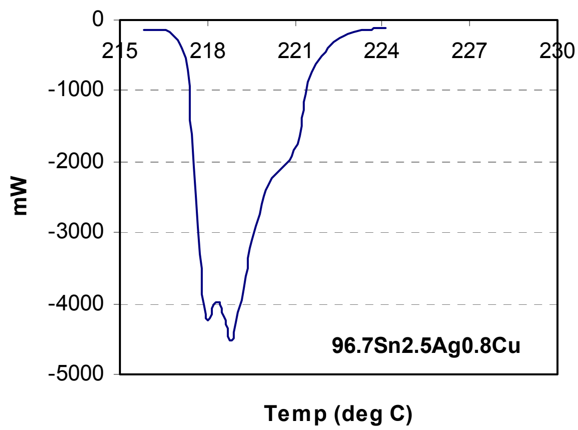

Figure 10 - DSC Thermograph of 96.7Sn2.5Ag0.8Cu

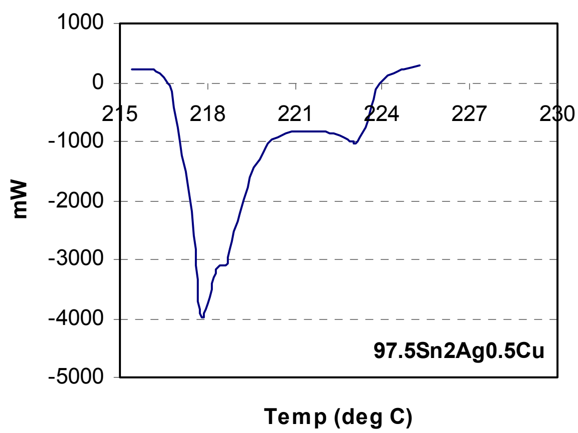

Figure 11 - DSC Thermograph of 97.5Sn2Ag0.5Cu

The data show that both 95.5Sn3.8Ag0.7Cu and 95.5Sn3.5Ag1Cu exhibit a single melting peak, with the former exhibiting a trace of tail at the high temperature end. At Ag content below 3.5%, the melting peak gradually broadens up and a double or multiple peaks endotherm gradually appears with further decrease in Ag content in the SnAgCu alloys.

The complexity of endotherms appears to correlate with the low tombstoning rate data, with broader peak corresponding to a lower tombstoning rate.

The splitting large endothermic melting peak has been attributed as the cause for the reduced tombstoning frequency for SnPb solders[1-3] and SnAgX solders[4, 5] in reflow soldering. The rationale of the anti-tombstoning effect using alloys with multiple peaks are listed as follows:

(a) A single sharp endothermic peak reflects an instantaneous melting of the solder upon reaching the melting temperature. This would allow a rapid wetting to the component termination by the low viscosity liquid solder. In the event of having unbalanced temperature distribution at the two ends of a component, an unbalanced wetting would be resulted thus causing tombstoning.

(b) A twin, or multiple peaks endotherm in the DSC curve indicates a melting behavior with multiple stages, or a melting process involving a viscous pasty transient stage. This viscous transient pasty stage results in a slower wetting, thus allows only a slow progressing in wetting. Consequently this results in a more homogeneous wetting on both ends of the component or a lower tombstoning frequency.

(c) The 95.5Sn3.5Ag1Cu is virtually identical as the true ternary eutectic point 95.6Sn3.5Ag0.9Cu of the SnAgCu alloys.[9] As discussed above, the instantaneous melting behavior of this eutectic alloy is prone to have a high tombstoning rate, as indicated by the maximum tombstoning rate within the SnAgCu alloys studied (see Figure 3).

Surface Tension

The surface tension of the SnAgCu alloys has been measured using a wetting balance tester, with results shown in Figure 12. Within the SnAgCu alloys system, the low surface tension correlates with the high tombstoning rate. Presumably the high tombstoning rate is attributed to the better spreading and therefore a better wetting promised by the low surface tension of liquid solder.[8]

It is interesting to note that 63Sn37Pb exhibits a tombstoning rate comparable with 95.5Sn3.8Ag0.7Cu regardless of its lower surface tension versus that of SnAgCu alloy. Presumably the fast wetting driving force for tombstoning caused by low surface tension is offset by the weak pulling force again caused by low surface tension. More work is needed in order to elucidate the relationship between surface tension and tombstoning rate when comparing solders with significantly different compositions.

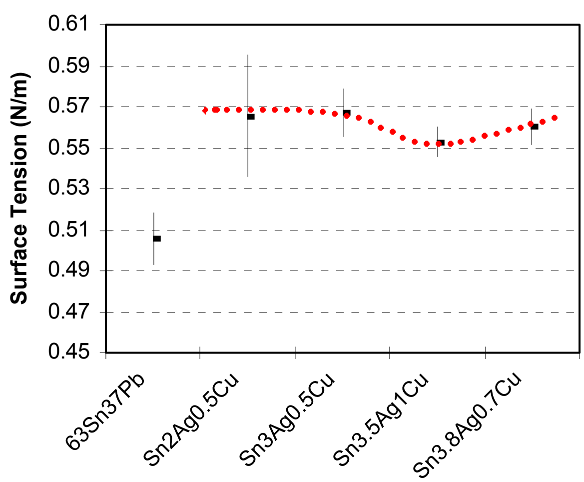

Figure 12 - Surface Tension of 63Sn37Pb and SnAgCu Alloys determined at 245°C and 260°C, Respectively

Discussion

1. In this study, vapor phase reflow was used to aggravate the tombstoning rate. The mechanism and relative tombstoning rate of samples are expected to be the same as other reflow technologies, such as forced air convection or conduction methods.[8]
2. The DSC of 95.5Sn3.8Ag0.7Cu (see Figure 7) shows a trace of tail when compared with 95.5Sn3.5Ag1Cu. This is consistent with the findings of Handwerker,[10] as illustrated by Figure 13. The considerable difference in tombstoning rate indicates the significant impact of a small fraction of solid phase at the onset of solder melting.

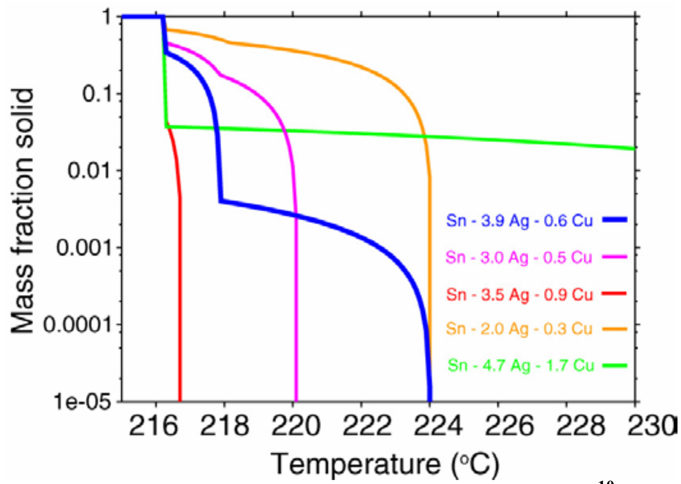

Figure 13 - Melting behavior of SnAgCu alloys[10]

3. The composition of alloys in this study mainly varies in Ag content. The tombstoning rate appears to decrease with increasing deviation in Ag content from the ternary SnAgCu eutectic composition. Copper content appears to have a negligible effect.
4. For SnAgCu solder system, a high Ag content not only costs more, but also tends to promote Ag_3Sn intermetallic platelet formation.[11] Therefore, to reduce the tombstoning rate of SnAgCu solders, a low Ag content, such as 2.5Ag, appears to be a more favorable choice.

Conclusion

Tombstoning of SnAgCu is affected by the solder composition. At vapor phase soldering, both wetting force and wetting time at a temperature well above the melting point have no correlation with the tombstoning behavior. Since tombstoning is caused by unbalanced wetting force, the results suggest that the tombstoning may be dictated by the wetting at the onset of paste melting stage. A maximal tombstoning rate is observed at 95.5Sn3.5Ag1Cu. The tombstoning rate decreases with increasing deviation in Ag content from this composition. DSC study indicates that this is mainly due to the increasing presence of pasty phase in the solders, which is expected to result in a slower wetting speed at the onset of solder paste melting stage. Surface tension plays a minor role, with lower surface tension correlates with a higher tombstoning rate. SnAgCu composition with a Ag content lower than 3.5%, such as 2.5Ag, is more favorable in terms of reducing tombstoning rate with minimal risk of forming Ag_3Sn intermetallic platelet.

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