Interfacial Reactions of Cu-Containing Lead-Free Solders with Au/NiP Metallization

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Cu-containing solder alloys have been used to identify their interfacial reactions with electroless NiP. As-reflowed, $AuSn_4$ intermetallic compounds (IMCs) are formed in the Sn-Cu and Sn-Ag-Cu solders, but in the cases of Sn-Ag-Cu-In, In-Sn-Au IMCs are formed and are uniformly distributed in the solder. Different types of IMCs such as high-Cu (>30 at.%), medium-Cu (30–15 at.%), and low-Cu (<15 at.%) containing IMCs are formed at the interface. High-Cu and medium-Cu containing ternary intermetallic compounds (TIMCs) are found in the Sn-Cu and Sn-Ag-Cu solder joints, respectively. Medium-Cu containing quaternary intermetallic compounds (QIMCs) are found in the Sn-Ag-Cu-In joints. Initially, TIMCs and QIMCs have higher growth rates, resulting in the entrapment of some Pb-rich phase in the high-Cu containing TIMCs and some In-Sn-Au phase in the QIMCs. High-Cu containing TIMCs have a lower growth rate and consume less of the NiP layer. The spalling of medium-Cu containing TIMCs in the Sn-Ag-Cu solder increases both the growth rate of TIMCs and the consumption rate of the NiP layer. Low-Cu containing QIMCs in the Sn-Ag-Cu-In solder are stable on P-rich Ni and reduce the dissolution rate of the NiP layer. Consumption of the NiP layer can be reduced by adding Cu or In, because of the changes of the interfacial IMCs phases, which are stable and adhere well to the P-rich Ni layer during reflow.

Key words: Intermetallics, lead-free solder, dissolution of electroless NiP, Cu-containing solder

INTRODUCTION

Au/NiP/Cu under bump metallization (UBM) is commonly used in ball-grid array (BGA) packages because of its excellent solderability, corrosion resistance, uniformity, low cost, selective deposition without photolithography, and also because it acts as a good diffusion barrier layer.[1,2] Lead-bearing solders, which have been widely used in electronics and automobile products, have been one of the main targets for replacement with nontoxic substances. Therefore, establishing lead-free solders has become a critical issue. According to a report on Pb-free alloys by the National Center for Manufacturing Science, Sn-Ag, Sn-Ag-Cu, and Sn-Cu solders have been suggested as promising candidate lead-free solders.[3] The Sn-Ag-Cu ternary eutectic solder has the lowest melting temperature (~217°C), good wettability, improved creep resistance, long thermal fatigue life, and has been accepted widely for use worldwide.[4,5] Sn0.7Cu solder is also one of the most popular lead-free solders because of its advantages of low cost, high shear strength, good creep resistance, and longer thermal fatigue life.[6,7] The Cu changes the IMC phases from Ni-Sn binary intermetallic compounds (BIMCs) to Sn-Cu-Ni ternary intermetallic compounds (TIMCs) and prevents the redeployment of Au to the interface.[6,8] The In, Bi, and Ge are used to lower the melting temperature of solders. In-containing solders give slow crack propagation, good wetting behavior, an increase in alloy strength, and good fatigue resistance.[9–12] Already, In-based solders are being used for interconnections in microwave devices.[13] In-51In solder possesses the advantages of high ductility, improved fatigue resistance, and good wettability.[11] Cheng et al. reported that the strength of Sn-3.8Ag-0.7Cu solder

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joints were higher than that of Sn-20In-2Ag-0.5Cu solder joints.[14] The formation of $AuIn_2$ compounds prevents the formation of more brittle intermetallic compounds such as $AuSn_4$ in the bulk solder.[15] In-15Pb-5Ag solder has a higher strength and a lower thermal coefficient of expansion than those of pure In and it reduces the embitterment by Au.[16] The Au embrittlement can be curtailed for In-49Sn solder joints because of the lower solubility of Au in the In-Sn alloy.[12] It has thus been established that both Cu and In have significant desirable effects on the growth rate of IMCs and the consumption of UBM. The effects of using combined additions of Cu and In are investigated thoroughly and, in particular, the reliability of the solder joints created is tested. In this study, the interfacial reactions such as IMC formation and the consumption rate of UBM between the liquid Sn-Cu, Sn-Ag-Cu, and Sn-Ag-Cu-In solders with a NiP substrate were investigated at a temperature of 250°C for different reflow times to determine effect of Cu-containing solders on the NiP UBM.

EXPERIMENTAL PROCEDURE

A Cu pad is a part of the internal wiring within a flexible BGA substrate. The solder mask opening chosen had a diameter 0.650 mm at the ball pad. Electroless Ni was deposited on the Cu pad. Immersion Au plating was immediately layered on the top of the NiP layer to avoid oxidation of the nickel surface. The P content of electroless Ni substrate was controlled by the pH value of the plating solution. The thickness of electroless Ni was about 4.6 μm with a P content of about 16 at.%, the Au layer thickness was about 0.6 μm, and the Cu layer thickness was about 15 μm. Preparation of flexible substrate and plating of NiP/Au on Cu pad were performed in the compass Technology Company Ltd., Hong Kong.

SOLDER BALL ATTACHMENT AND CHARACTERIZATION

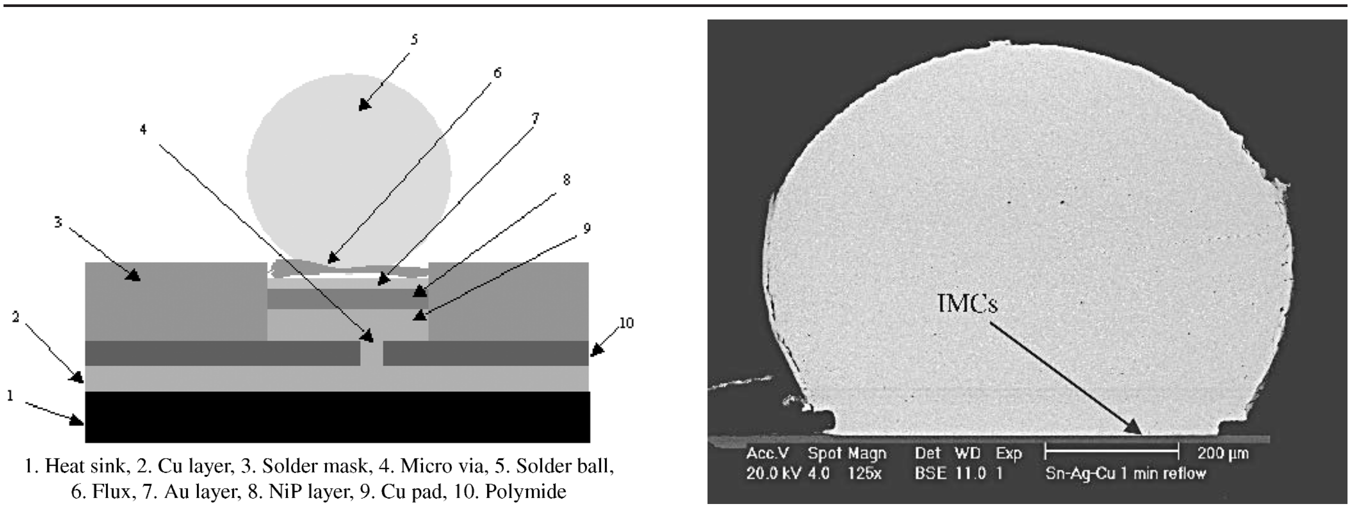
The solder joints were made between flexible substrates with Cu/NiP/Au coated pads and lead-free Sn-Cu, Sn-Ag-Cu, and Sn-Ag-Cu-In solders. The compositions of the solders were Sn0.7Cu, Sn3.5Ag0.5Cu, and Sn3.5Ag0.5Cu9In (wt.%). The melting temperatures were ~227°C, ~217°C, and ~207°C for the Sn-Cu, Sn-Ag-Cu, and Sn-Ag-Cu-In solder, respectively. The solder balls were placed on the prefluxed coated pads (Fig. 1a) and then reflowed at 250°C in a reflow oven (BTU, model VIP-70N). No-clean flux was used on the pads. After the reflow process, the samples were held at the same temperature (i.e., 250°C) for 5 min, 10 min, 30 min, 120 min, and 180 min.

To investigate the microstructure of the samples, they were sectioned using a slow speed diamond saw and then mounted in epoxy. The cross-sectioned samples were ground and polished carefully and then gold sputter coated for examination. Chemical and microstructural analyses of the gold-coated cross-sectioned samples were obtained using a Philips XL 40 FEG scanning electron microscope (SEM) equipped with energy-dispersive x-ray (EDX) analysis equipment (EDAX International, model DX-4). The dissolution rate of the electroless NiP layer was determined by measuring the remaining NiP layer thickness after each reflow condition. The backscattered electron mode of SEM was used for the cross-sectional study.

RESULTS AND DISCUSSION

Dissolution Kinetics and Cross-Sectional Studies of the Interface

To investigate the reaction kinetics of the electroless NiP/solder joints, detailed cross-sectional studies were carried out by SEM. During reflow, molten solder reacts with the Au/NiP/Cu layer and forms different types of IMCs at the interface. These interfacial IMCs together with the unreacted NiP layer provide the adhesion between the solder and the substrate (Fig. 1b). The IMC phases were determined by EDX analyses, as detailed subsequently.



1. Heat sink, 2. Cu layer, 3. Solder mask, 4. Micro via, 5. Solder ball, 6. Flux, 7. Au layer, 8. NiP layer, 9. Cu pad, 10. Polymide

a b

Fig. 1. (a) Solder ball is placed on the prefluxed coated pad and (b) IMCs provide adhesion between the solder and the substrate after as-reflowing.

Interfaces As-Reflowed

In the cases of Sn-Cu and Sn-Ag-Cu solders, during the reflow process, molten solders absorb the entire Au layer into solution and form Au-Sn IMCs in the solder and also form different types of interfacial IMCs at the interface (Figs. 2 and 3). From EDX analysis, high-Cu containing TIMCs (at.% $Sn_{48}Ni_{17}Cu_{35}$) and medium-Cu containing TIMCs (at.% $Sn_{57}Ni_{18}Cu_{25}$) are found in the Sn-Cu and Sn-Ag-Cu solder joints, respectively (Fig. 2a and b). The thicknesses of the TIMCs are almost the same. A trace of Pb (≤0.05wt.%, Aoki Laboratories Ltd.) is found in the Sn0.7Cu solder as an impurity and appeared as a Pb-rich phase (white region) in the bulk solder and even in the high-Cu TIMCs (Figs. 2a and 3a).[6] In the In-containing solder joints, molten solder reacted with the Au layer and formed an In-Sn-Au IMC (Figs. 2c and 3c). The atomic percentage composition of the IMC was $In_{0.48}Sn_{0.25}Au_{0.27}$. The In-Sn-Au IMC was uniformly distributed in the solder. The EDX analysis established that the medium-Cu containing QIMCs have formed at the interface.[14,17] The atomic percentage of the QIMCs was $Sn_{0.51}Cu_{0.26}Ni_{0.20}In_{0.03}$. A small amount of In-Sn-Au IMCs have been entrapped into the QIMCs (Figs. 2c and 4c). This is thought to be due to the slower diffusion rate of Au in the In-containing solder as compared to that in the Sn-Cu and Sn-Ag-Cu solder.[12,16] A very thin dark P-rich Ni layer was also found between the IMCs and the NiP layer (Fig. 2a, b, and c). The P content in the dark P-rich Ni layer was close to the stoichiometry of Ni_3P.[18] The EDX analysis identified the composition (at.%) of newly appeared IMCs such as $Ag_{0.80}In_{0.15}Sn_{0.05}$, $Ag_{0.36}In_{0.22}Sn_{0.42}$, and $Sn_{0.54}Cu_{0.36}In_{0.10}$ found in the In-containing solder (Figs. 2c and 3c). Sn-Cu and Au-Sn IMCs were found in the Sn-Cu and Sn-Ag-Cu solder. Ag-Sn IMC was also found in the Sn-Ag-Cu solder (Fig. 3a and b). However, these IMCs were not found in the In-containing solder.[14] Indium thus suppresses the formation of these IMCs. The growth rates of TIMCs and QIMCs were higher and consumed more of the NiP layer. The morphology of the TIMCs and QIMCs were very rough.

Interfaces after Long-Time Molten Reactions

A reflow time for industrial applications above 10 min may not be realistic for practical processes. However, in this study, up to 180 min was used. The main purpose of this extended time in the molten state or reflow time is the scientific interest in establishing a database, which can than be helpful in predicting life and for designing new components.

After a 30-min reflow, it was seen that the thickness of IMCs and the P-rich Ni layer increased, whereas the original NiP layer thickness decreased (Figs. 4, 6a, b, and 7). The thickness of high-Cu containing TIMCs in the Sn-Cu solder was slightly lower than the medium-Cu containing TIMCs in the Sn-Ag-Cu solder joints (Figs. 4a, 4b, 6a, and 7). The growth rates of TIMCs in the solder joints are diffusion controlled.[14] Figure 5a shows that Cu_6Sn_5 compounds have formed with a specific shape in the Sn-Cu solder. The formation of high-Cu containing TIMCs is insufficiently fast to consume all the Cu atoms from the liquid of Sn-Cu solder. When the percentage of Cu at any site reaches the threshold limit for Cu_6Sn_5 compound formation (i.e., around

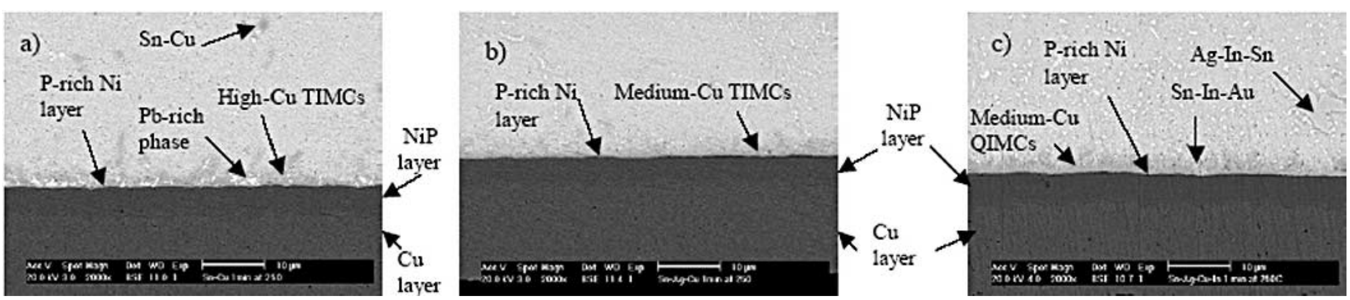


Fig. 2. Interfacial reactions of NiP/solder as-reflowed (a) interface of a NiP/Sn-Cu solder joint, (b) interface of a NiP/Sn-Ag-Cu solder joint, and (c) interface of a NiP/Sn-Ag-Cu-In solder joint.

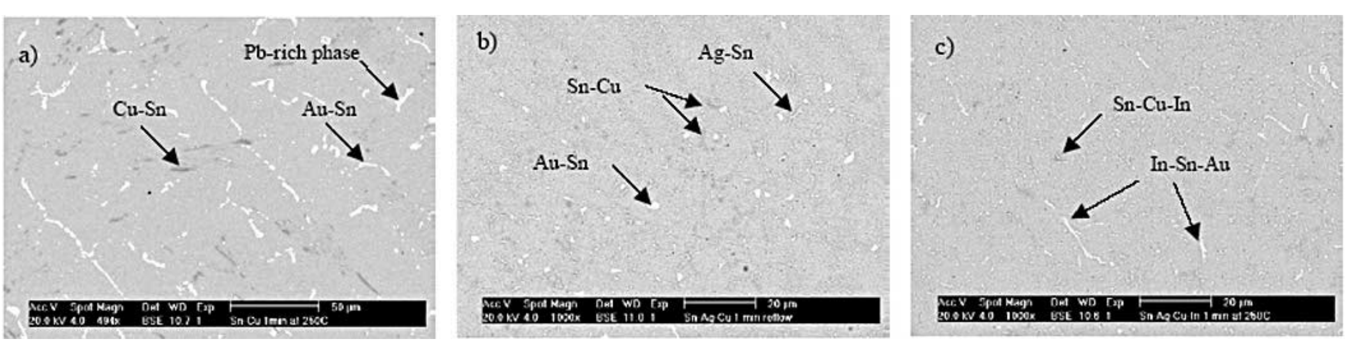


Fig. 3. Different types of IMCs in the Cu-containing solder during as-reflowed: (a) Sn-Cu, (b) Sn-Ag-Cu, and (c) Sn-Ag-Cu-In solders.

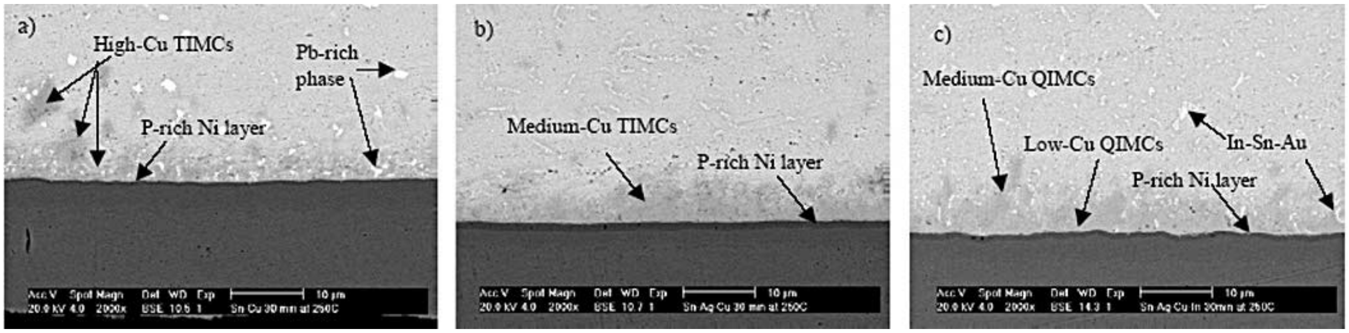


Fig. 4. Interfacial reactions of NiP/solder after 30 min reflow: (a) interface of a Sn-Cu solder joint, (b) interface of a Sn-Ag-Cu solder joint, and (c) interface of a Sn-Ag-Cu-In solder joint.

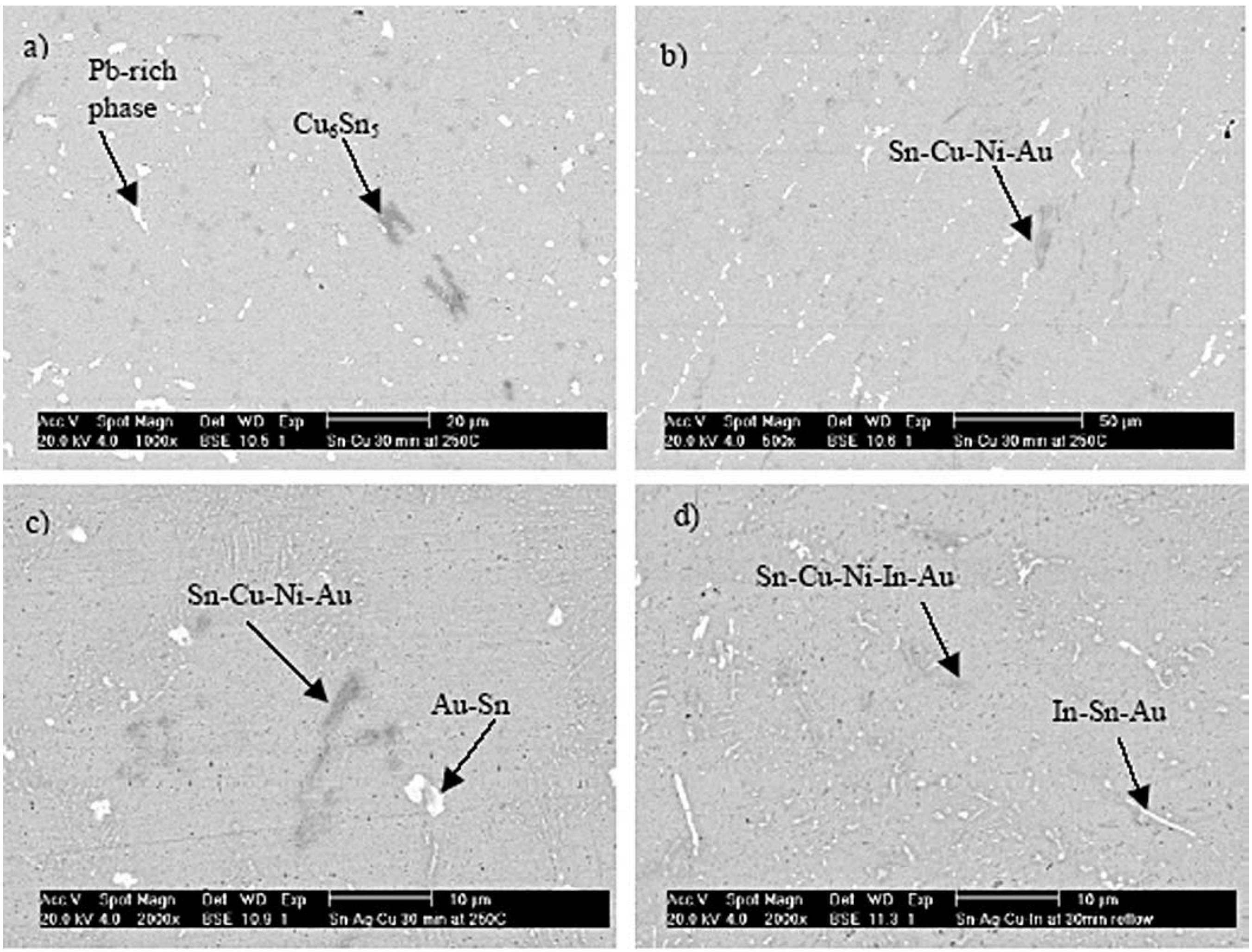


Fig. 5. (a) Cu_6Sn_5 IMCs with a specific shape in a Sn0.7Cu solder, and (b)–(d) Ni-containing IMCs in a Cu-containing solder after 30-min reflow.

39wt.%Cu according to the Cu-Sn phase diagram), Cu-Sn IMC precipitates in the bulk solder.[19] In the case of the In-containing solder, the thickness of QIMCs was 6.93 μm. The growth rate of QIMCs was lower than that for medium-Cu containing TIMCs (Figs. 4b, 4c, and 6a). There may be two reasons for this: (1) the formation of more stable compounds in the In-containing solder, and (2) the entrapment of In-Sn-Au phases in the Sn-Cu-Ni-In QIMCs may have some effect on the diffusion of atoms. At this stage, low-Cu containing QIMCs were found between the medium-Cu containing QIMCs and the P-rich Ni layer at the interface. The atomic percentage of low-Cu containing QIMCs was $Sn_{0.60}Ni_{0.27}Cu_{0.08}In_{0.05}$. Ni-containing IMCs such as Sn-Cu-Ni-Au and Sn-Cu-Ni-In-Au IMCs were found in the Cu-containing solder (Fig. 5b–d). It was seen that some Ni atoms have diffused through the interfacial IMCs and formed Ni-containing compounds in the solder.[6] Sn-In-Au, Ag-In-Sn, and Sn-Cu-Ni-In-Au IMCs were

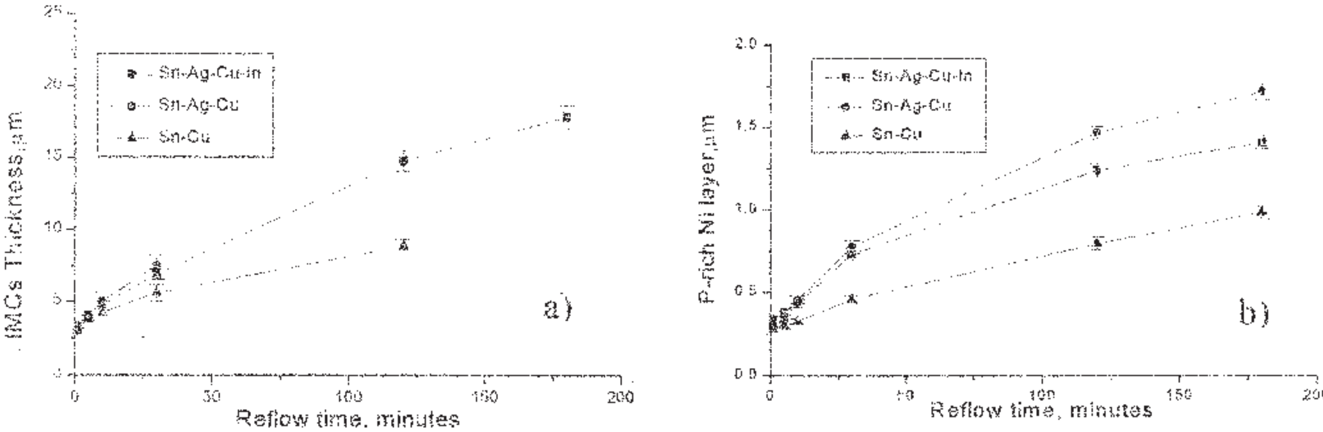


Fig. 6. (a) Thickness of IMCs with reflow times and (b) P-rich Ni layer thickness with reflow time.

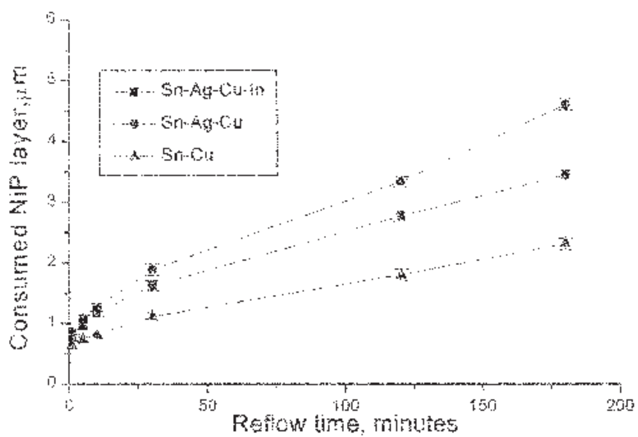


Fig. 7. Amount of NiP layer thickness consumed with reflow time.

found within the In-containing solder. This suggests that Sn-Cu-Ni-In-Au IMCs are more stable than Sn-Cu-In and Sn-Cu-In-Au IMCs within the solder. The thickness of the P-rich Ni layer was lower for the In-containing solder joint than for the Sn-Ag-Cu solder joint. The Sn-Cu solder showed a lower growth rate of high-Cu containing TIMCs and a lower P-rich Ni layer thickness than all the other solders (Fig. 6). Thus, the consumption rate of the NiP layer was lower in the NiP/Sn-Cu solder system.

In the NiP/Sn-Cu solder system, spalling of needle-shaped high-Cu TIMCs was observed from the solder-side TIMCs after 120-min reflow (Fig. 8a). The thickness of high-Cu containing TIMCs did not increase significantly. In the case of Sn-Ag-Cu solder, a larger amount of spalling of medium-Cu containing TIMCs was observed, with an increase in the diffusion rate of atoms and formation of TIMCs at the interface, which was accompanied by an enhanced dissolution rate of the NiP layer (Fig. 8b and 7). The possible reasons for this spalling of medium-Cu containing TIMCs in the NiP/Sn-Ag-Cu system are as follows: (1) high-Cu containing TIMCs may be more dense than the medium-Cu containing TIMCs, thus the first diffusion of atoms and interfacial reactions increases the dissolution rate of the NiP layer and the thickness of TIMCs, resulting in the greater spalling of medium-Cu containing TIMCs from the interface.[20,21] (2) Slightly brighter (in the SEM image) low-Cu containing (about 8.5 at.%) TIMCs formed between the medium-Cu containing TIMCs and the P-rich Ni layer (Fig. 8b), due to a lower supply of Cu from the Sn-Ag-Cu solder suggesting that medium-Cu containing TIMCs may not be stable on low-Cu containing TIMCs during extended reflow; (3) spalling may be due to the larger volume change between the medium-Cu containing TIMCs and P-rich Ni layer in this case compared to the other solder joints;[2] (4) the changes of interfacial energies between the P-rich Ni layer and low-Cu containing TIMCs, between low-Cu containing TIMCs and medium-Cu containing TIMCs layer, and between the medium-Cu containing TIMCs and

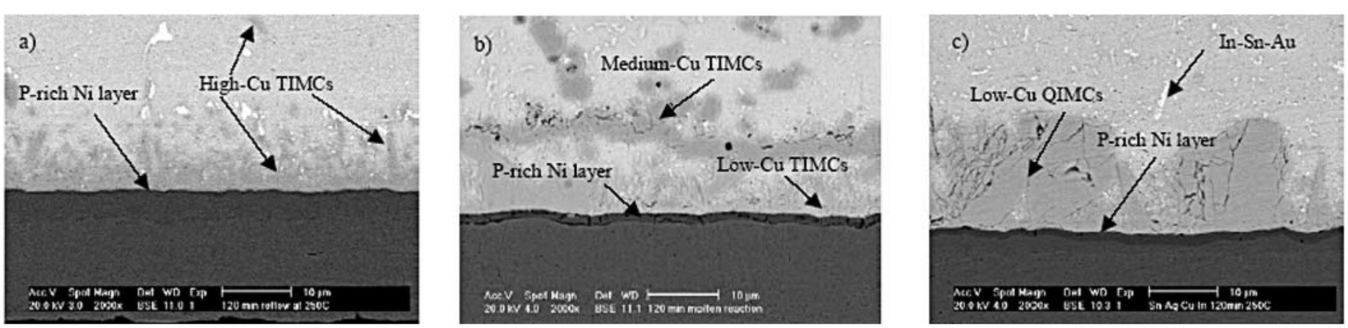


Fig. 8. Interfacial reactions of NiP/solder after 120-min reflow: (a) interface of a NiP/Sn-Cu solder joint, (b) interface of a NiP/Sn-Ag-Cu solder joint, and (c) interface of a NiP/Sn-Ag-Cu-In solder joint.

the molten solder will have an effect on the morphology and may influence the degree of spalling.[2,22] In the case of the NiP/In-containing solder system, after 120 min of reflow, it was found that most of the scalloplike QIMCs were stable and adhered well to the P-rich Ni layer (Fig. 8c). From EDX analysis, the atomic percentage of the solder-side QIMCs was $Sn_{0.59}Ni_{0.30}Cu_{0.09}In_{0.02}$ and near the P-rich Ni layer was $Sn_{0.57}Ni_{0.33}Cu_{0.08}In_{0.02}$. The compositions in terms of all atom species were almost the same in all places on the QIMCs. The spalling of low-Cu containing QIMCs was also observed in the In-containing solder but was lower than for the medium-Cu containing TIMCs in the Sn-Ag-Cu solder.

In the case of the Sn-Cu solder, after 180 minutes reflow, it was seen that high-Cu containing TIMCs were stable and adhered well to the P-rich Ni layer (Fig. 9a). The thickness of high-Cu containing TIMCs did not increase due to a lower growth rate and spalling of the TIMCs from the solder side. No medium-Cu and low-Cu containing TIMCs were found at the interface of the NiP/Sn-Cu solder system. Low-Cu, medium-Cu, and high-Cu containing TIMCs were found in the Ni/Sn-Cu solder system,[6] and it has also been reported that low-Cu containing TIMCs are found in the NiP/Sn-Ag-Cu solder system. Two possible reasons may be offered for such growth behavior of TIMCs in the NiP/Sn-Cu solder system: (1) formation of a P-rich Ni layer between the TIMCs and the NiP layer, which acts as a good diffusion barrier layer. (2) The growth rate of TIMCs is lower in the NiP/Sn-Cu solder system than that in the Ni/Sn-Cu and NiP/Sn-Ag-Cu solder systems. In the case of the Sn-Ag-Cu solder, after 180 min of molten reaction, it was seen that the entire NiP layer had been consumed and in some places an intermediate Ni-Sn-P layer was observed between the low-Cu containing TIMCs and the P-rich Ni layer (Fig. 9b). The thicknesses of the slightly brighter (in the SEM image) low-Cu containing TIMCs and the P-rich Ni layer increased significantly. In some places, the P-rich Ni layer broke creating channels. These channels are the result of the coalescence of the Kirkendall voids formed during the diffusion process.[18,23] Thus, the diffused Sn atoms came into contact with the Cu pads through these channels and reacted to form Ni-Sn-Cu and then Cu-Sn IMCs. By these means, the dissolution rate of NiP layer was increased (Fig. 7). The EDX analysis revealed that Ni-Sn-Cu IMCs formed under the broken P-rich Ni layer. In the case of the In-containing solder, it was seen that low-Cu containing QIMCs were stable and adhered well to the P-rich Ni layer (Fig. 9c). The thickness of low-Cu containing QIMCs was 14–23 μm. The thicknesses of the P-rich Ni layers were 1.72 μm, 1.41 μm, and 0.986 μm for the Sn-Ag-Cu, In-containing solder, and Sn-Cu solder, respectively (Figs. 6b and 9a–c).

The NiP layer after 180 min reflow for Sn-Cu solder joints was still intact (2.31 μm). High-Cu containing TIMCs had a lower growth rate and consumed the NiP layer at a lower rate. The average consumption rate of NiP was 0.0128 μm/min. A thickness of 3.45 μm of the NiP layer took part in the reaction with the In-containing molten solder and formed a different type of IMC in the solder and at the interface. The average consumption rate of the NiP layer was 0.0191 μm/min. In the case of the Sn-Ag-Cu solder, 4.6 μm of the NiP layer has consumed during 180-min reflow. The average consumption rate of the NiP layer was 0.0255 μm/min, which is 1.335 times and 1.992 times higher than for the In-containing solder and Sn-Cu solder, respectively.

Effect of Elements and Formation of New Phases

Table I shows the different types of IMCs, which have formed during reflow and extended time reflow. Cu-Sn, Au-Sn, and Ag-Sn IMCs were found in the solders, which do not contain In, but these were not found in the In-containing solder. Ag-Sn, Ag-In, and In-Au IMCs were not found, but new Ag-In-Sn and In-Sn-Au IMCs were found in the In-containing solder, which may be due to a lower percentage of In addition in the solder examined here. Many investigators have found Ag_2In and $AuIn_2$ IMCs in In-containing solders perhaps due to the addition of a higher percentage of In (<20 wt.%) to the solder than the case examined here.[12,16,24] The Cu-Sn compounds were not stable within the Sn-Cu and Sn-Ag-Cu solders during extended reflow. Therefore,

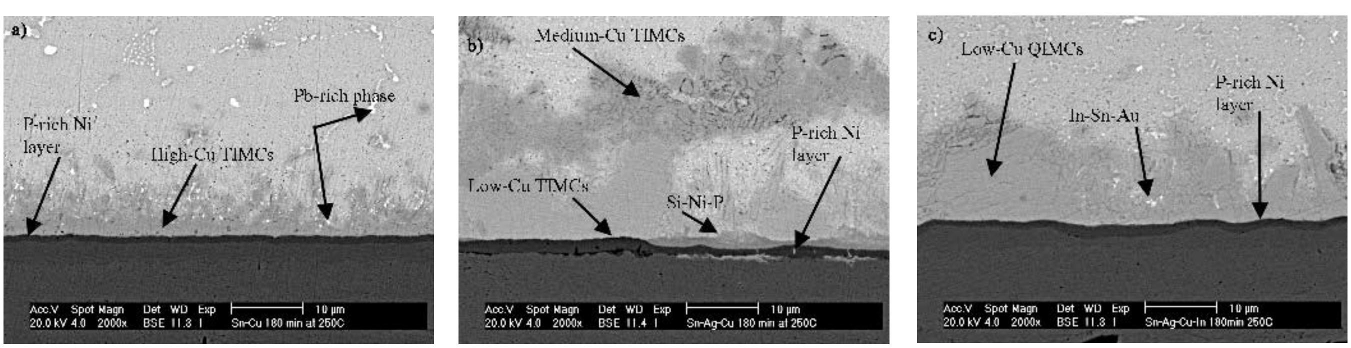


Fig. 9. Interfacial reactions of NiP/solder after 180-min reflow: (a) interface of a NiP/Sn-Cu solder joint, (b) interface of a NiP/Sn-Ag-Cu solder joint, and (c) interface of a NiP/Sn-Ag-Cu-In solder joint.

Table I. Formation of IMCs during Reflow

During As-Reflowed		
Solder	**Interfacial IMCs**	**IMCs within the solder**
Sn-Cu	High-Cu containing TIMCs	Sn-Cu, Au-Sn
Sn-Ag-Cu	Medium-Cu containing TIMCs	Sn-Cu, Ag-Sn, Au-Sn
Sn-Ag-Cu-In	Medium-Cu containing QIMCs	Sn-Cu-In, Ag-In-Sn, Au-Sn-In

During Extended Reflow		
Solder	**Interfacial IMCs**	**IMCs within the Solder**
Sn-Cu	High-Cu containing TIMCs	Sn-Cu-Au, Sn-Cu-Ni-Au, Au-Sn
Sn-Ag-Cu	Medium-Cu containing TIMCs, Low-Cu containing TIMCs	Sn-Cu-Au, Sn-Cu-Ni-Au, Ag-Sn, Au-Sn
Sn-Ag-Cu-In	Low-Cu containing QIMCs	Sn-Cu-Au-In, Sn-Cu-Ni-Au-In, Ag-In-Sn, Au-Sn-In

Cu-Sn-Au and the more stable Sn-Cu-Ni-Au IMCs were formed within the solder. In the case of the In-containing solder, Sn-Cu-In IMCs were not stable during extended reflow. Therefore, Sn-Cu-In-Au and the more stable Sn-Cu-Ni-In-Au IMCs were formed within the solder. These Cu-containing compounds prevent the redeployment of Au to the interface. In-Sn-Au IMCs formed rapidly at the interface and were uniformly distributed in the solder. The formation of In-Sn-Au compounds prevented the formation of more brittle IMCs such as $AuSn_4$ in the bulk In-containing solder. A larger amount of Au was found in the very white (in the SEM image) In-Sn-Au IMC. A small amount of In-Sn-Au IMC was entrapped by the QIMCs due to the lower diffusion rate of Au in the In-containing solder. The diffusion of Au was faster through the Sn-Cu and Sn-Ag-Cu than it was through the In-containing solder.

During extended times of reflow, the growth rates of IMCs in the Cu-containing solder joints were ranked as high-Cu containing TIMCs $<$ medium-Cu containing QIMCs $<$ medium-Cu containing TIMCs. High-Cu containing TIMCs had a lower growth rate and a lower consumption rate of the NiP layer during extended reflow (Figs. 6a and 7). There was no appreciable difference of Cu, Sn, Ni, and In content through the thickness of the low-Cu containing QIMCs with extended reflow. All atoms could diffuse through the low-Cu containing QIMCs at a fast rate. Low-Cu containing QIMCs were stable on the P-rich Ni layer and reduced the dissolution rate of the NiP layer. In the case of the Sn-Ag-Cu solder, low-Cu containing TIMCs were found at the interface in the later stage of reflow due to reduced supplies of Cu from the solder for the formation of more stable compounds within the solder and at the interface. Medium-Cu containing TIMCs had a higher growth rate, more spalling, and consumed more of the NiP layer. High-, medium-and low-Cu containing IMCs had a significant effect on the dissolution rate of the NiP layer and the thickness of IMCs at the interface.

CONCLUSIONS

The interfacial reactions at solder joints, the formation and growth of IMCs, and the dissolution of the NiP layer were investigated during extended reflow of Sn0.7Cu, Sn3.5Ag0.5Cu, and Sn3.5Ag0.5Cu9In solders with NiP layers.

Formation of more stable Cu-containing compounds in the solder prevents the redeployment of Au at the interface of the solder joints. In-Sn-Au IMCs form rapidly at the interface and a small amount of the In-Sn-Au IMC was entrapped in the QIMCs due to a lower diffusion rate of Au in the In-containing solder. Cu-Sn, Ag-Sn, and Au-Sn IMCs were not found in the In-containing solder. Different types of new IMCs were (Sn-Cu-Ni-In, Ag-In-Sn, In-Sn-Au, Sn-Cu-In, Sn-Cu-In-Au, and Sn-Cu-Ni-In-Au) found at the interface and in the solder due to the addition of Indium (9 at.%) in the solder. The formation of In-Sn-Au compounds prevented the formation of more brittle IMCs such as Au-Sn in the bulk In-containing solder. In the reflow process, the growth rates of TIMCs and QIMCs were very high and more of the NiP layer was consumed. During extended reflow, the growth rates of IMCs depended on the percentage of Cu. High-Cu containing TIMCs had a lower growth rate than the medium-Cu containing TIMCs and the medium-Cu containing QIMCs. The dissolution rate of the NiP layers depended on the growth rate and spalling of the IMCs. Medium-Cu containing TIMCs had a higher growth rate and were not stable on the low-Cu containing TIMCs and the P-rich Ni layer. The higher spalling of medium-Cu containing TIMCs in the Sn-Ag-Cu solder increased the growth rate of TIMCs and the dissolution rate of the NiP layer. High-Cu containing TIMCs and low-Cu containing QIMCs were stable and adherent on the P-rich Ni layer and reduced the dissolution rate of the NiP layer. The dissolution rate of the NiP layer with the Cu-containing solders was ranked as Sn-Ag-Cu>Sn-Ag-Cu-In>Sn-Cu solder. Therefore, it could be said that the resistance of the NiP layer as a barrier for Sn is lower for the

Sn-Ag-Cu solder than for the Sn-Cu and Sn-Ag-Cu-In solders. Thus, small additions of alloying elements have significant effects on the changes of IMCs at the interface, on the growth rate of IMCs, and on the dissolution rate of the NiP layer. In order to reduce significantly the consumption rate of NiP UBM, Sn0.7Cu solder is recommended, and in order to reduce both the process temperature and the consumption rate of NiP UBM, Sn3.5Ag0.5Cu9In solder alloy is recommended.

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