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Suppressing the growth of Cu–Sn intermetallic compounds in Ni/Sn–Ag–Cu/Cu–Zn solder joints during thermal aging

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ABSTRACT

This study aims to investigate the interfacial reactions and cross-interaction of Ni/Sn–3.0Ag–0.5Cu/Cu–*x*Zn (Ni/SAC/Cu–*x*Zn; $x = 0$, 15, and 30 wt.%) solder joints. In comparison with the Ni/SAC/Cu solder joint, Ni/SAC/Cu–15Zn and Ni/SAC/Cu–30Zn solder joints revealed thinner Cu_6Sn_5-based intermetallic compounds (IMCs) at both Ni/SAC and SAC/Cu–Zn interfaces after aging at 150 °C for 40 days. $(Cu,Ni)_6(Sn,Zn)_5/(Cu,Ni)_6Sn_5$ dual-phase formed at the Ni side, while $(Cu,Ni)_6(Sn,Zn)_5$ single-phase at the Cu–Zn side. Interestingly, the interfacial IMCs grew very slowly, and no void formed in these Zn-contained solder joints during the heating process. Also, the dissolved Zn in the solder alloy reduced the elemental cross-interaction between Ni and Cu–Zn substrates. The noticeable thermal stability of Ni/SAC/Cu–Zn solder joints is attributed to the Zn redistribution retarding the reaction of Ni, Cu and Sn. Phase formation and IMCs suppression mechanisms in Ni/SAC/Cu–Zn solder joints were probed and discussed.

1. Introduction

Flip-chip and ball-grid array (BGA) packaging technologies have been widely used for the micro-electronic package. Solder alloys usually connect two different metal pads, e.g. electrolytic Ni/Au [1,2] and organic surface preservative (OSP) Cu [1–3], respectively on the chip-side and packaging-side. The Ni/solder/Cu sandwich structure is a common material sequence in solder joint assemblies [1–6]. When the Sn-based solders, e.g. Sn–Ag–Cu, Sn–Cu and Sn–Ag alloys, reacted with the Ni and Cu substrates, two reactions were occurred at the Ni/solder and solder/Cu interfaces, accompanying with the formation of Cu–Ni–Sn ternary intermetallic compounds (IMCs) [2–5]. Additionally, the cross-interaction would affect the interfacial reactions. The cross-interaction was attributed to the diffusion of Cu and Ni atoms through the solder alloy from one side to the other side between Cu and Ni substrates [2–6]. Liu et al. reported various microstructures and microhardness across the Ni/Sn/Cu sandwich structure during the reflow process [5,6].

In the Ni/Sn–Ag–Cu/Cu solder joint system, the $(Cu,Ni)_6Sn_5$ IMC with different Ni concentration formed at both Ni/Sn–Ag–Cu and Sn–Ag–Cu/Cu interfaces [2]. During thermal aging, the interfacial IMCs grew rapidly, and Kirkendall voids often formed at the solder/Cu interface. In general, the IMC has brittle nature [7]. Literature shows that too thick IMC and lots of voids at the joint interface give rise to serious reliability concerns [7,8]. For drop testing, cracks easily propagated through the $(Cu,Ni)_6Sn_5$ IMC [9]. In order to improve the solder joint reliability, the thickness of IMC should be controlled, and the voids should be inhibited. Replacing the Cu substrate material for metal pad by Cu-based alloys is an approach. Previous studies proofed that the solder/Cu–Zn joint is superior to the solder/Cu one for soldering [10–17]. In comparison with the solder/Cu joint, the solder/Cu–Zn joint displays the thin interfacial IMC [10–14], void-free interface [10–15], and refined microstructure in the solder [15,16]. The interfacial segregation and embrittlement of bismuth in Sn–Bi/Cu–Zn are eliminated [17]. Most importantly, the drop reliability of the Cu–Zn/solder/Cu–Zn assembly is strengthened obviously [14].

In this study, the Ni/Sn–3.0Ag–0.5Cu/Cu–Zn (Ni/SAC/Cu–Zn) solder joints were designed to improve the thermal stability of the original Ni/Sn–3.0Ag–0.5Cu/Cu (Ni/SAC/Cu) solder joint. The interfacial reactions and the cross-interaction are correlated to the elemental distribution, the composition variation and the Sn grain orientation.

2. Experimental procedures

Ni/Sn–3.0Ag–0.5Cu/Cu–*x*Zn (Ni/SAC/Cu–*x*Zn; $x = 0$, 15, and 30 wt.%) solder joints were prepared by a two-step reflowing process, as shown in Fig. 1. In the first reflowing step, the SAC solder balls (18 mg) were reflowed on Ni substrates, with 3 mm × 3 mm

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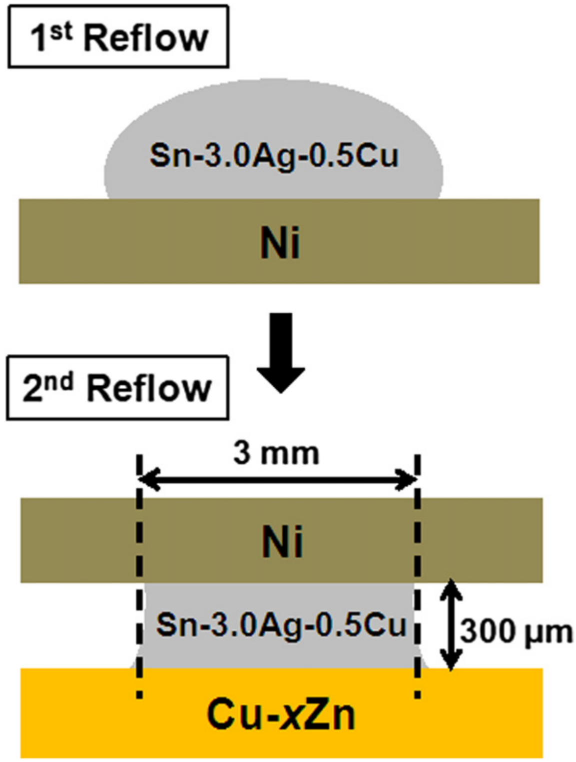

Fig. 1. Schematic plot of the Ni/SAC/Cu–*x*Zn sample preparation.

reaction area, at 250 °C for 1 min. In the second reflowing step, these Ni/SAC solder joints were reflowed on Cu, Cu–15Zn, and Cu–30Zn substrates, respectively, with identical reaction area (3 mm × 3 mm), at 250 °C for 1 min. The bump high is around 300 μm. The Cu–15Zn and Cu–30Zn substrate alloys were produced by smelting at 1200 °C in an Ar-atmosphere and homogenizing at 600 °C for 10 days. These two Cu–Zn alloys are single-phase solid solution, and their composition is measured by field-emission electron probe microanalysis (FE-EPMA, JXA-8500F, JEOL). Then, these as-reflowed samples were aged at 150 °C in an oven for 10, 20 and 40 days to evaluate the microstructural variation and elemental redistribution in solder joints under heating. To analyze the interfacial microstructure of Ni/SAC/Cu–*x*Zn solder joints, these samples were cold-mounted in the epoxy, and the cross-section samples were prepared by grinding, polishing and ion-beam milling (RES-101, BAL-TEC). Field-emission scanning electron microscopy (FE-SEM, JSM-7600F, JEOL) was used to observe backscattered electron (BSE) images. FE-EPMA was used to measure the composition of phases and elemental distribution in solder joints. The average thickness of interfacial IMCs was estimated from BSE cross-sectional images by using image-analysis software. In addition, the Sn grain orientation imaging microscopy (OIM) map was obtained using electron backscattering diffraction (EBSD).

3. Results and discussion

3.1. Interfacial microstructural evolution and phase formation

Figs. 2 and 3 show the microstructure at the interfaces of Ni/SAC/Cu, Ni/SAC/Cu–15Zn and Ni/SAC/Cu–30Zn solder joints before and after aging at 150 °C for 40 days, respectively. Intermetallic compounds with various morphologies formed at both Ni/SAC and SAC/Cu–*x*Zn interfaces. FE-EPMA quantitative analysis identified these phases as Cu_6Sn_5-based IMCs, and no Ni_3Sn_4-based IMC was found in these three solder joints, as listed in Tables 1and 2. During reflow, Ni would dissolve from Ni substrates into Cu_6Sn_5, substituting some part of Cu site in the lattice to form $(Cu,Ni)_6Sn_5$. The driving force for the dissolution of Ni into $(Cu,Ni)_6Sn_5$ is attributed to the decrease of the formation energy [18,19].

In the Ni/SAC/Cu, two kinds of $(Cu,Ni)_6Sn_5$ with different Ni concentration formed at the Ni/SAC interface. The $(Cu,Ni)_6Sn_5$ IMC with lower than 10 at.% Ni is represented as the symbol of L-$(Cu,Ni)_6Sn_5$, while the higher Ni-contained (>22 at.%) one is indicated as the symbol of H-$(Cu,Ni)_6Sn_5$. $(Cu,Ni)_6Sn_5$ with variation of Ni contents in the range of 10–22 at.% was not discovered in this study. In fact, both L-$(Cu,Ni)_6Sn_5$ and H-$(Cu,Ni)_6Sn_5$ phases were also detected in Ni/Au/SAC/Cu assemblies [2]. The formation of L-$(Cu,Ni)_6Sn_5$ and H-$(Cu,Ni)_6Sn_5$ is related to the amount of Cu atoms supplied from the SAC solder alloy and Cu substrate. During the first reflowing step, the SAC solder reflowed with the Ni substrate, and limited Cu atoms from the SAC solder reacted with Sn and the Ni substrate to form H-$(Cu,Ni)_6Sn_5$ at the Ni/SAC

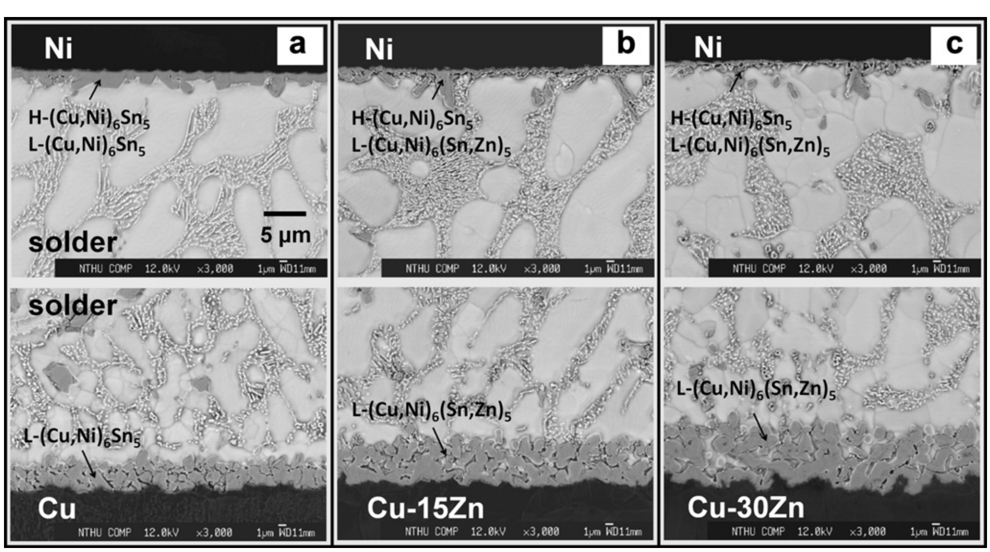

Fig. 2. Interfacial microstructure of (a) Ni/Sn–Ag–Cu/Cu, (b) Ni/Sn–Ag–Cu/Cu–15Zn, and (c) Ni/Sn–Ag–Cu/Cu–30Zn solder joints before aging.