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The dominant effect of *c*-axis orientation in tin on the electromigration behaviors in tricrystal Sn-3.0Ag-0.5Cu solder joints

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ABSTRACT

Copper atoms have a higher diffusivity along the *c*-axis than along the *a*-axis of the tin grain during electromigration (EM). The growth behavior of intermetallic compounds (IMCs) in tricrystal Sn3.0Ag0.5Cu ball grid array (BGA) solder joints under EM was investigated. The results show that the *c*-axis direction can significantly affect the IMCs growth behavior in a tricrystal solder joint both in the solder matrix and at the interfaces under EM. The IMCs in the solder matrix and the IMCs at the cathode grow along the electron flow direction to the *c*-axis direction. When the *c*-axis direction was along the electron flow direction to the positive direction of ND, the IMCs grew to the cross sectioned surface. However, when the *c*-axis direction was along the electron flow direction to the negative direction of ND, the IMCs would grow to the inner solder matrix. Moreover, it seems that, in a tricrystal solder joint, the IMCs growth behavior of one grain is not affected by the other two grains with nearly 60° misorientations.

1. Introduction

Recently, the continuous development of miniaturization and high-performance [1] in electronic packaging demand a long lifetime for in electronic device. However, due to the diminished sizes in packaging, the size of solder joints was greatly reduced [2], which were expected to be downsized to1 μm from current 100 μm in future [3–5]. Consequently, the current density through the solder joints would be up to 10^6 A/cm^2 [3]. Therefore, electromigration behavior has become a main reliability issue in electronic packaging due to the miniaturization of electronic device leading to the downsizing of solder joints [6]. Furthermore, polarization effect, voids, and tin whisker growth would occurred under the migration of metal atoms driven by the electron wind force during electromigration, so the reliability of solder joints made a significant effect on the electronic packaging [2,7–9].

In a tin-based solder joint, it involves a variable nucleation under cooling for tin in the process of solidification [10–11]. The nature of solidification in SnAgCu (SAC) lead-free alloys often leads to one or three tin grains generated in solder joints [12–15]. There is a highly anisotropic behavior in mechanical, electrical and diffusion properties of tin grain due to the body-centered tetragonal crystal structure with a lattice constant of a = b = 5.83 Å and c = 3.18 Å. Certain transition metals, including Au, Ag, Cu, and Ni, diffuse faster along *c*-axis than the other two orthogonal directions in tin grains, exhibiting very pronounced anisotropy [16–19]. Thus, the electromigration-induced failure by diffusion anisotropy in tin grain is considered as a more vital problem than by local current crowding effect [3].

Recently, more attentions were paid on the influence of tin grain orientation which induced the electromigration of solder joints. Lee et al. [20] reported that the tin orientation played a significant effect at the dissolution of under bump metallization (UBM) and IMCs of Cu_6Sn_5 undergoing electromigration. Huang et al. [3] found that the Cu_6Sn_5-type protrusions formed in specific tin grains when the angle θ (between the direction of electron flow and the *c*-axis in tin grain) was relatively small. And the protrusions were not in the neighbor grains with large angle θ or along the direction of *c*-axis in tin grain. Kao et al. [21–23] reported that the substrate dissolution was caused by the diffusivity of Ni atoms in tin grain. Yang et al. [16] reported that the effect of grain orientation on the growth behavior of IMC layer at the interface. However, these studies mainly focused on the effect of angle θ between the *c*-axis and the electron flow direction on the dissolution of interfacial IMC layer. Few study reported the influence of the *c*-axis direction in tin grain on the growth direction of IMCs at the solder matrix [24]. And the effect of *c*-axis orientation on the growth direction of interfacial IMC layer has not been reported.

During the process of reflowed, the specific misorientation angle with 60° was preferentially formed in tin-based solder joints, which was consistent with the research results of Telang [12,25]. In addition, almost all high-angle grain boundaries have tricrystal misorientation (57°–63°) [26]. Tasooji et al. [27–28] reported that the tin grain

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boundary misorientation had a significant effect on electromigration owing to the higher diffusivity along grain boundary than that of lattice. Thus, the electromigration behavior in single grained and tricrystal solder joints could have different performance. Shen et al. [29–30] found Cu played a significant important role in interfacial Cu-Sn IMCs rapidly growth and dissolution because they were mostly cyclic twins. However, few researchers reported the electromigration behavior at a tricrystal solder joint with the effect of *c*-axis orientation in tin grain.

In this study, two tricrystal solder joints were selected as objects to investigate the distribution of IMC particles in solder matrix, as well as the evolution of interfacial IMC layer in a practical BGA component. The solder joints were cross-sectioned to track the electromigration behavior. In addition, the microstructure evolution and the tin grain orientation were conducted by a FEI QUANTA FEG 650 scanning electron microscopy (SEM) with an Aztec HKL electron backscattered diffraction (EBSD) detector. The component elements of interfacial IMC layers were identified by a BRUKER Energy Dispersive Spectrometer (EDS) QUANTAX. The effect of tin grain *c*-axis on the electromigration of Cu/Ni-SAC305/Cu tricrystal solder joints was investigated in terms of Cu migration and IMC particles generation in the solder matrix.

2. Experimental procedures

A practical chip-scale packaged (CSP) ball grid array (BGA) solder joint sample with a lead-free composition of Sn-3.0Ag-0.5Cu was investigated in this study. The BGA component dimensions were 12 mm × 12 mm × 1 mm. Fig. 1 shows the vertical view X-ray transmission image of the BGA component. The BGA component involved hollow 22 × 22 Sn3.0Ag0.5Cu solder balls with 0.3 mm ball size in diameter at 0.5 mm pitch. The BGA packages were soldered onto the non-solder mask defined (NSMD) Cu pad of a FR-4 printed circuit board (PCB) using a typical reflow profile with peak temperature of 245 °C and a dwell time of 1 min at temperature above 217 °C. The solder bumps on the chip side had a daisy-chained interconnection structure with the Cu pad on the PCB side after welding. The Ni UBM on the BGA chip side was 6 μm. The BGA component was cross-sectioned, and then 22 half-sized solder joints were ground and polished following without

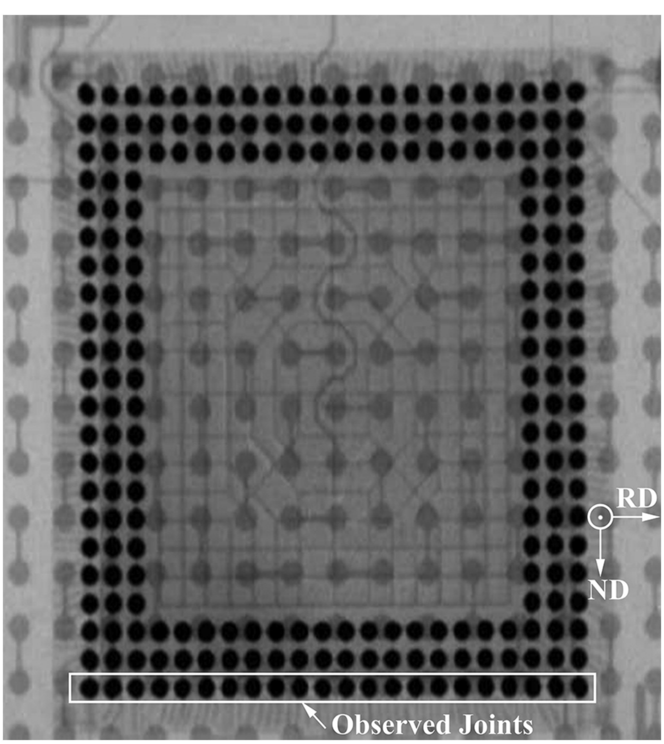

Fig. 1. The vertical view X-ray transmission image of BGA component.

being mounted on the epoxy. The current stressing test was conducted at room temperature (25 °C) for 600 h. The current density was 2.1×10^3 A/cm^2 subjected to the 22 half-sized solder joints, and direction of current in two adjacent solder interconnects was different, as shown in Fig. 2. What's more, the eleventh and fifteenth solder joints were both tin-based tricrystal orientation, which were selected the research objects in this study, named as No. 11 and No. 15 solder joints (red color in Fig. 2).

After the electromigration test, all of the cross sectioned solder joints were subjected to a metallographic grinding and polishing process with 0.05 μm Al_2O_3 suspensions for characterization. The SEM was used to characterize the microstructure evolution of solder joints which were as-reflowed and after polished. The thickness of interfacial IMC layers was measured by the Photoshop® software. The phase color could be considered as a distinction between interfacial IMC layers and copper pads as well as solder matrix. Therefore, the interfacial IMC layers which processed same phase color were selected by the Photoshop® software. Moreover, the area and the length of the interfacial IMC layers were measured by the Photoshop® software, so the thickness of the interfacial IMC layers could be obtained. In addition, the EBSD examination was carried out to characterize the orientation of β-tin grains.

3. Results and discussion

3.1. Grain orientation of as-reflowed solder joints

Due to the high anisotropy of tin grain, which would significantly affect electromigration behavior in tricrystal solder joints. Thus, the β-tin orientation of solder joints was characterized by EBSD before and after electromigration. Fig. 3(a) and (b) shows the orientation (with grain boundaries) of β-tin in cross sectioned Nos. 11 and 15 solder joints. The green line represented the low angle grain boundaries which was larger than 2° and less than 5°. The blue line represented the low angle grain boundaries which was larger than 5° and less than 15°. What's more, the red line represented the high angle grain boundaries which was larger than 15°. Therefore, the cross-sectioned solder joint was divided into two main grains, grains A and B in No. 11. According to the pole figure in Fig. 3(c), the two main β-tin grains and some stray tin grains in the No. 11 as-reflowed cross sectioned solder joint, and the misorientation angle distribution showed that the maximal misorientation angle was nearly 60° in Fig. 3(e). The results indicated that the two β-tin grains had a tricrystal orientation relationship. Furthermore, Fig. 7(d) and (f) show the pole figures and the misorientation angle distribution of No. 15 solder joint, respectively. It indicates that the No. 15 solder joint also contained two main grains at the cross-sectioned surface, named as grains C and D. Moreover, the two grains of C and D at the cross-sectioned surface were tricrystal orientation relationship. In addition, the unit cells representing the grain orientation of grain A, B, C, and D were showed in Fig. 3(a) and (b), respectively.

3.2. Microstructure evolution of solder joints after electromigration

Fig. 4 shows the morphology of interfacial IMC layers and the microstructure of cross sectioned as-reflowed No. 11 and No. 15 solder joints, respectively. The upper side of solder joint was the Ni UBM chip side, and the lower side was the Cu pad side. As shown in Fig. 4(a) and (b), the backscattered electron (BE) image of Nos. 11 and 15 showed that a typical eutectic microstructure in the solder matrix after reflowed. As shown in Fig. 4, there were numerous Cu_6Sn_5 IMC particles randomly participated within the tin-based solder joints. In addition, some small size Ag_3Sn IMC particles dispersed uniformly in the matrix. At the same time, as shown in Fig. 4, a thin irregular IMC layer at the solder/Ni UBM interface and a continuous scallop shape IMC layer at the solder/Cu pad interface formed in the as-reflowed solder joints. The compositions of the interfacial IMC layers on the chip side in the two