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Electromigration in thin-film solder joints

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ABSTRACT

Intermetallic compound (IMC) formation and growth are critical reliability issues with interconnected microelectronics, especially for small-scale solder joints in three-dimensional integrated circuits (3D IC) packaging. In this study, the growth behavior of IMCs in ultrathin 3D-IC solder joints under electromigration was investigated using a field-emission scanning electron microscope (FE-SEM) equipped with an electron backscatter diffraction (EBSD) analysis system. The joints consisted of a Cu/Sn/Cu configuration with a Sn thickness of ~30 μm. We determined a strong dependence of the IMC growth and Cu pad depletion on the β-Sn orientation upon electron current stressing. When the *c*-axis of the Sn grain was oriented in the direction of the electron flow, aggressive Cu–Sn IMC growth and Cu pad depletion occurred at the anode and cathode, respectively. A mathematical analysis based on crystallography and electromigration theory was used to rationalize the strong dependences that were observed.

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1. Introduction

Due to the toxic effects of Pb oxide, Pb-containing solders (e.g., eutectic Pb–Sn) have been widely replaced by Pb-free alloys in microelectronic packaging in recent years. Because most Pb-free solders are Sn-based alloys containing more than 90 wt.% Sn (e.g., Sn–Ag–Cu series of solders), the physical/chemical properties of the Pb-free solder joints are inevitably dominated by the properties of bulk Sn [1]. Solid Sn possesses a body-centered tetragonal (BCT) structure (space group: $I4_1/amd$) with a lattice constant of $a = b = 5.83$ Å and $c = 3.18$ Å at temperatures above 13 °C [2], which is generally termed β-Sn or white Sn. Unlike the face-centered cubic (fcc) crystal structure of Pb, the anisotropic β-Sn can produce different physical/chemical characteristics in relation with the individual crystal axis, e.g., Young's modulus [3], resistivity [4], and diffusivity [1,4,5]. In terms of anisotropic diffusion behavior, the Cu diffusivity is approximately 2×10^{-6} cm^2/s at 25 °C along the Sn *c*-axis, which is 500 times faster than that along the *a*- or *b*-axis [5] and is approximately 10^{12} times the Sn self-diffusion rate [5]. Additionally, the Ni diffusivity along the Sn *c*-axis is orders of magnitude ($\sim 3 \times 10^4$ times) faster than that along the *a*-axis at 150 °C [1]. As high Sn-content solders tend to form large Sn grains during the solidification, the crystallographic orientation of Sn determines the properties of the entire solder joint.

A strong dependence of the metallization pad depletion on the β-Sn orientation and specific grain boundaries was recently reported in the literature [6–9]. Lu et al. [6] investigated the correlation between Ni(P) depletion and Sn orientation in a current stressed Cu/Ni(P)/solder/Cu/Ni/TiW/Cu line structure. Because the *c*-axis was aligned with the electric current, the rapid interstitial diffusion of Ni and Cu dissociated the intermetallic compound (IMC) and swept it to the Sn grain boundaries or through the grain to the opposite side of the solder joint, which resulted in serious depletion of Ni(P)/Cu at the cathode [6]. Interestingly, a serrated cathode (Cu) depletion can be induced by a high current density with preferential dissolution along the grain boundaries of the interfacial Cu_6Sn_5 layer [7]. In contrast, the failure of solder joints due to Sn self-diffusion or lattice diffusion occurred when the *c*-axis was at a large angle with respect to the current direction, where the diffusion rates of Cu and Ni in Sn were slow [6]. The failure mode in this case was void formation neighboring the solder/IMC interface rather than pad depletion [6]. Kang et al. [8] discovered that rapid electromigration of Cu and Ni atoms through high-angle grain boundaries (44–95°) of Sn damaged the metallization pads and reduced the lifetime of the solder joints. A subsequent study by Chen et al. [9] indicated that several Cu_6Sn_5 particles can selectively form within specific Sn grain boundaries upon current stressing due to the imbalance of inward and outward fluxes of Cu, resulting from the anisotropic electromigration behavior of Cu in Sn.

The incessant trend toward ultrathin electronics necessitates a continuous shrinkage in the solder joint size. Currently, the electronic industry is developing ultrathin solder joints for through-Si-via (TSV) technology in 3-dimensional integrated circuits (3D IC) packaging, and the joint diameter is only a few tenths microns [10]. As the sizes of solder joints reduce to such a scale, the current density loaded in the power solder joints will increase significantly, and the numbers of Sn grains and grain boundaries in one single joint will decrease accordingly. Therefore, the diffusion of Cu (or Ni) via the Sn lattice plays an even more important role in the electromigration reliability issues.

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There is an urgent need to initiate a study on the electromigration effect in ultrathin solder joints, specifically on pad depletion and IMC growth behaviors. This study aimed to provide useful information for researchers and engineers attempting to optimize the microelectronic interconnections to protect against electromigration.

2. Experimental details

The electromigration behavior in the 3D-IC scale solder joints, specifically focusing on pad depletion and IMC growth issues, was investigated in this study. The solder joints possessed a Cu/Sn/Cu configuration with a Sn thickness of ~30 μm, as shown in Fig. 1. Upon current stressing, a direct current (DC) with a global mean current density of 10^4 A/cm^2 was applied at 150 °C in the Sn region. After current stressing for a scheduled time period (t), the surfaces of the solder joints were slightly polished using Al_2O_3 powder (particle size: 0.3 μm) first and then was subjected to an oxide polishing treatment using colloidal silica with a grain size of approximately 0.04 μm and a pH value of about 9.8, to remove the oxides/scratches for the subsequent analysis. An optical microscope (OM) in both bright-field and cross-polarized imaging modes and a field-emission scanning electron microscope (FE-SEM, JEOL7001F) equipped with an electron backscatter diffraction (EBSD, EDAX/TSL Technology) analysis system were used to obtain microstructural and crystallographic information. In the EBSD analysis, ND (normal direction), RD (rolling direction), and TD (transverse direction) denoted the direction normal to the polished surface, normal to the Cu/Sn/Cu interface, and parallel to the Cu/Sn/Cu interface, respectively; specifically, the direction of the electric current was parallel to the RD and perpendicular to the TD upon current stressing, as illustrated in Fig. 1. Additionally, a field-emission electron probe microanalyzer (FE-EPMA, JEOL JXA-8500F) was used to determine the composition of each phase and elemental distribution in the current stressed couple.

3. Results

Fig. 2 shows the microstructures of a Cu/Sn/Cu couple after current stressing of 10^4 A/cm^2 at 150 °C for 0 h (a–b) and 120 h (c–d). The direction of electron flow is indicated by an arrow labeled e^-. Prior to the current stressing test (i.e., $t = 0$ h), a symmetric growth of scallop-type Cu_6Sn_5 with a thickness of ~2 μm at both interfaces can be noted in Fig. 2(a). Additionally, there were numerous isolated domains with sizes ranging from submicrons to a few microns scattered in the Sn matrix (Fig. 2a). These domains were identified using EPMA to be Cu_6Sn_5. The dissolved Cu was precipitated as Cu_6Sn_5 domains due to the solubility limit in the solidification process of soldering. Fig. 2(b) shows a cross-polarized image corresponding to Fig. 2(a), which illustrates the Sn orientation distribution in different colors. It was observed that the solder matrix consisted of Sn grains with various orientations and sizes ranging from ~7 μm to a few tenths microns. Interestingly, in some regions, the solder joint was spanned by one single Sn grain along the RD (as indicated in Fig. 1), which indicates that the 3D-IC scale solder joint consisted of only a few Sn grains in the thickness direction prior to the current stressing test.

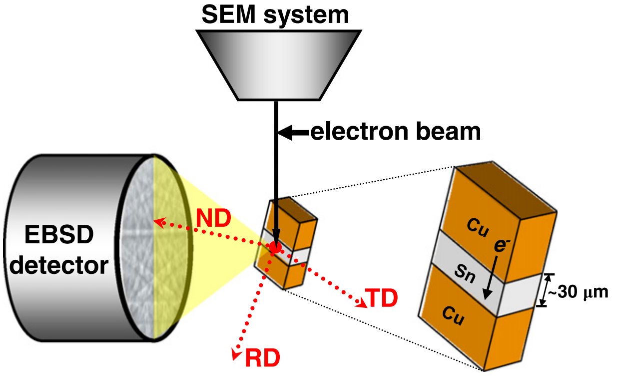

Fig. 1. Schematic drawing illustrating the Cu/Sn(~30 μm)/Cu diffusion couple in the EBSD analysis. The electric current is indicated by an arrow labeled e^-.

After 120 h of current stressing, the thicknesses of Cu – Sn IMCs (Cu_6Sn_5 and Cu_3Sn) increased at the anode, whereas that decreased at the cathode, accompanied by a large depletion of the Cu substrate, as shown in the optical microscopy (Fig. 2c) and FE-EPMA X-ray mapping of Sn (Fig. 2d). This observation agrees well with the "polarity effect of electromigration" reported previously in the literature [11,12]; however, the growth of Cu_6Sn_5 at the anode did not exhibit a typical layered structure but instead had a wavy morphology. In a few regions, the Cu_6Sn_5 had reached the cathode interface after 120 h of stressing, i.e., the entire Sn had been converted into Cu – Sn IMCs. It is generally reported that the Cu_6Sn_5 layer appears as a layered morphology in solder joints under a fixed current direction and current density case [11–13]. We concluded that the unique IMC morphology in the examined ultrathin solder joints resulted from various β-Sn orientations and that further investigation via EBSD should be conducted.

Fig. 3(a) shows a zoomed-in view of the Cu/Sn/Cu couple in Fig. 2(c). Fig. 3(b) provides the combined result of the EBSD image quality (IQ) and orientation map of Fig. 3(a). Different grain orientations are indicated by different colors, as reflected in the legend of Fig. 3(c)–(d). To reveal the phase distribution clearly, a broken line was utilized to depict the phase boundary between Sn and Cu_6Sn_5. Additionally, the orientations of the Sn grains were marked with the corresponding unit cells inserted at the locations of individual Sn grains in the EBSD map. The Sn matrix consisted of several large grains that are referred to as grains #1 to #5, as indicated in Fig. 3(b). The c-axes of grains #1, #4, and #5 were nearly aligned with the electric current, and the disorientation angles were determined by EBSD to be ~21.5°, ~41.2°, and ~26.4°, respectively; grains #2 and #3 possessed the c-axes with large angles (~86.5° and ~65.3°, respectively) with respect to the current direction.

β-Sn consists of a BCT structure with a highly anisotropic diffusion behavior [5]. Therefore, Cu atoms in grains #1, #4, and #5 (where the c-axes approximately aligned with the current direction and possessed large Cu diffusivities) may be rapidly driven away from the cathode interface of Cu/Sn/Cu upon current stressing, which results in regions unsaturated with Cu. This generated a Cu concentration gradient between the cathode Cu and the solder, and subsequently induced the dissolution of the Cu pad (or Cu – Sn IMCs) into the solder. The as-dissolved Cu atoms were then delivered to the anode interface as a result of electromigration, where they reacted with Sn and re-nucleated as Cu_6Sn_5. The above process repeated itself under DC stressing until all of the Sn was converted into Cu – Sn IMCs. In contrast with grains #1, #4, and #5, the opposite reaction occurred in grains #2 and #3 (i.e., less Cu depletion and Cu_6Sn_5 formation) because they possessed a c-axis nearly perpendicular to the current direction. Consequently, non-uniform Cu depletion at the cathode along with the wavy Cu_6Sn_5 growth at the anode was created in the current stressed ultrathin Cu/Sn/Cu joint, as shown in Fig. 3(a)–(b).

4. Discussion

A strong dependence of the Cu_6Sn_5 growth (anode side) and Cu pad depletion (cathode side) on the Sn orientation was observed in the current stressed Cu/Sn(~30 μm)/Cu couple, as shown in Fig. 3. To quantitatively analyze the effects of Sn orientation on these two aspects (i.e., IMC growth and pad depletion), we investigated the atomic flux during current stressing. A literature review revealed that electromigration of Cu may reduce the Cu_6Sn_5 (or Cu) at the cathode interface of Cu/solder/Cu through solid-state dissolution into the solder and increase the quantity at the anode interface by driving the as-dissolved Cu atoms through the solder media to nucleate as Cu_6Sn_5 [11–13]. Consequently, the Cu flux driven by the electrical force in the Sn matrix should be considered in the following

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