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The amorphous interphase formed in an intermetallic-free Cu/Sn couple during early stage electromigration

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ABSTRACT

The early stage athermal electromigration behavior at the heterogeneous interface of a Cu/Sn couple was investigated at room temperature. The material interaction formed an interphase consisting of an amorphous Cu-Sn matrix, enriched with Cu (87.6–93.4 at.% Cu) and embedded with a few nano-crystalline Cu cells. The Cu-rich characteristic of the interphase indicates atypical interdiffusion behavior. The formation of the interphase was governed by the electrodisruption of the cathode Cu lattices accompanying the interdiffusion between Cu and Sn atoms. The occurrence of the meta-stable interphase is believed to be a preliminary stage prior to the subsequent intermetallic formation.

Solder interconnects in microelectronic devices suffer from electromigration that raises serious reliability concerns [1–3]. Numerous studies have focused on the microstructural evolutions at various solder/metallization interfaces, especially the solder/Cu bilayer metal combination, during electric current stressing [4–11]. Electromigration has been shown to result in a massive consumption of Cu metallization [4, 5] and the formation of Kirkendall voids at the cathode solder/Cu interface [6, 7]. Electromigration also gives rise to a polarity effect on the growth of Cu-Sn intermetallic compounds (IMCs) at the interfaces between solders and electrodes [8, 9]. Phase transformation of interfacial Cu-Sn IMCs induced by electromigration has also been reported in previous investigations [10, 11]. Considering the future development of microelectronic packaging toward the miniaturization of solder interconnects [12–14], a rising current density applied in solder interconnects is anticipated, so the undesirable phenomena that occur during electromigration as mentioned above may become intensive.

In the studies mentioned above [4–11], the microstructural evolutions at the solder/Cu interface were investigated under conditions where interdiffusion and IMC formation had already occurred prior to the electric current stressing. To the best of the authors' knowledge, no study has ever contributed to the investigation of the early stage electromigration behavior at the solder/Cu interface because of the difficulty in fabricating an IMC-free solder/Cu interface. The early stage material interaction at the solder/Cu interface may govern the subsequent nucleation and growth behavior of IMCs, and thus deserves comprehensive understanding and an in-depth investigation.

In the present study, an atomic-scale image across an IMC-free Cu/Sn interface was investigated using a spherical aberration corrected scanning transmission electron microscope (Cs-corrected STEM) to visualize the fundamental electromigration behavior. In comparison with the commonly used electroplating method, which results in the formation of Cu-Sn IMCs at the as-deposited solder/Cu interface [15–17], a magneton sputtering technique was applied in the present study to achieve an IMC-free interface prior to the electromigration experiment. In addition, the Joule heating effect also contributed to significant variations in the interfacial microstructure, revealing the non-negligible role of the specimen temperature during electric current stressing [18–20]. In the present study, a thin film structure (low cross-sectional area) of the Cu/Sn couple was applied to minimize the Joule heat generated by electromigration. It is anticipated that it would best reveal the athermal effect of electromigration on the Cu/Sn interface imposed by electron wind force at room temperature.

A Cu/Sn couple, as illustrated schematically with the dimensions shown in Fig. 1(a), was applied for the electromigration study. Fig. 1(b) shows the low-magnification bright field TEM image of the Cu/Sn couple. The patterned Cu/Sn couple was fabricated using magnetron sputtering, photolithography, and wet etching processes. A 50 nm thick Ti thin film was firstly deposited on a 4 inch Si wafer as an adhesion layer. A 500 nm thick Cu electrode was deposited on the Ti/Si substrate with the aid of photolithography and wet etching processes for the subsequent electromigration experiment. The following deposition of a 500 nm thick Sn layer on the patterned substrate formed the Cu/Sn couple, as shown in Fig. 1(a).

The Cu/Sn couple was stressed with a direct electric current at 6.0 $\times 10^4$ A/cm^2 for 1 h in an ambient atmosphere. The electron flow direction was from the cathode Cu to the anode Sn. The steady-state temperature of the specimen during electric current stressing was measured

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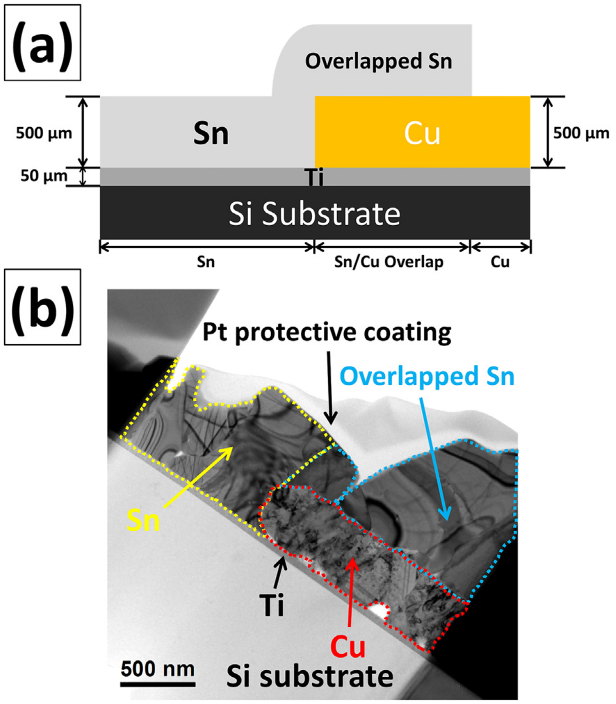

Fig. 1. (a) Schematic drawing (side-view) of the Cu/Sn couple with the dimensions (not scaled proportionally); (b) low-magnification bright field TEM image of the Cu/Sn couple corresponding to (a).

with a K-type thermocouple that was attached to the Cu/Sn interface. The steady-state temperature, measured to be 29.3 °C, was close to the ambient room temperature (25.5 °C), showing a slight temperature rise in the Cu/Sn couple induced by the Joule heating effect. The specimen was rapidly quenched with liquid nitrogen for 15 s before the electric current stressing was terminated to stimulate and obtain the *in situ* atomic-scale investigation across the Cu/Sn interface.

The microstructural and compositional analyses across the Cu/Sn interface after electromigration were investigated using a Cs-corrected STEM operated at 200 kV. The TEM specimens were prepared using a dual beam focus ion beam. The microstructure across the Cu/Sn interface was investigated using a bright field imaging mode. The atomic-scale image was further investigated using a high resolution imaging mode. The STEM high angle annular dark field (HAADF) imaging mode was also applied for the qualitative observation of the chemical constituents within the selected areas. The phase and crystal structure of the selected regions were characterized using a selected area electron diffraction (SAED) analysis with an analytical dimension of approximately 135 nm. The electron diffraction analysis was also investigated with the aid of a fast Fourier transform (FFT) treatment. The compositional analysis across the Cu/Sn interface was investigated using energy dispersive spectroscopy (EDS) equipped in the STEM. The electron spot size of the EDS measurement was theoretically 1.04 nm. The collection time for the point spectrum analysis was 30 s. For comparison purposes, the as-prepared Cu/Sn couple that was pre-annealed in the ambient atmosphere (25.5 °C) for 168 days prior to the STEM analysis was investigated as a thermal benchmark. The microstructure and chemical composition across the as-annealed Cu/Sn interface were investigated in comparison with those across the Cu/Sn interface after electromigration.

Fig. 2(a) shows the bright field TEM image of the enlarged view across the as-annealed Cu/Sn interface taken from Fig. 1(b). The Sn matrix across the longitudinal Cu/Sn interface exhibits a single crystal structure, as shown by the SAED pattern of Sn inset in the upper left corner of the figure. The Cu electrode exhibits a polycrystalline structure on the basis of the appearance of ring patterns, as shown by the SAED

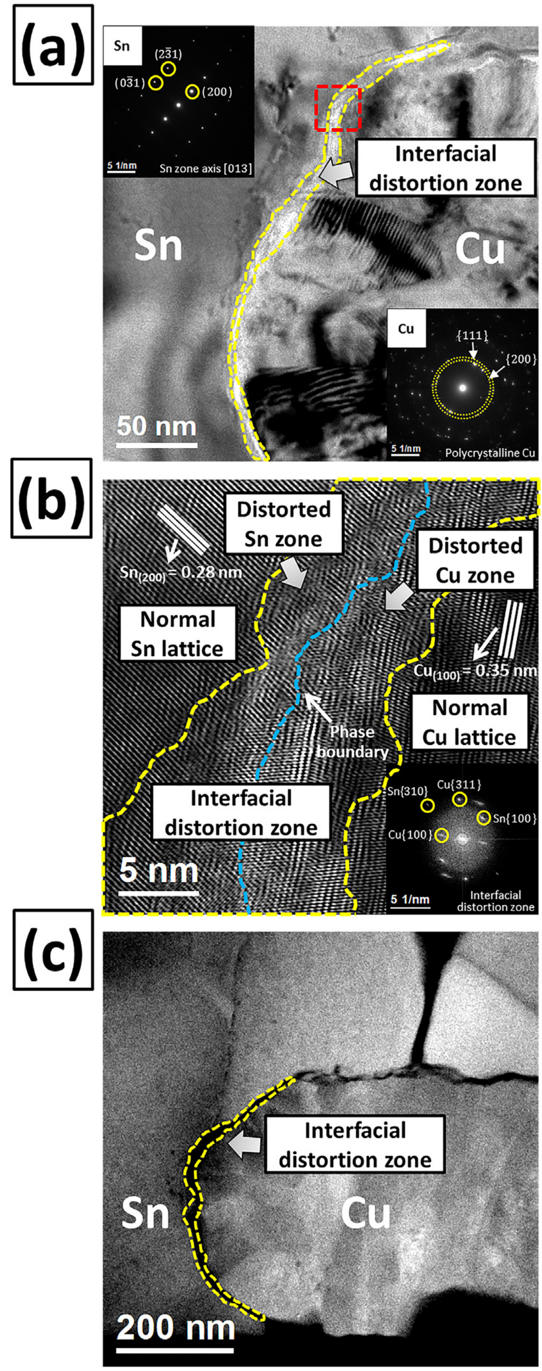

Fig. 2. (a) Bright field TEM image and the corresponding SAED patterns of Cu and Sn across the as-annealed Cu/Sn interface; (b) high resolution TEM image of the confined region (broken red square) in (a) and the inset FFT electron diffraction pattern of the interfacial distortion zone; (c) STEM HAADF image across the as-annealed Cu/Sn interface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pattern of Cu inset in the lower right corner of the figure. It can be seen that a thin nano-layer (broken yellow line) was formed at the Cu/Sn interface after room temperature annealing for 168 days. A high resolution image, shown as Fig. 2(b), taken from the confined region (broken red square) in Fig. 2(a) further characterizes the thin nano-layer to be an interfacial distortion zone that consists of distorted Cu and Sn lattices. A continuous phase boundary separates the distorted Cu and Sn lattices from each other, as marked in the figure. In comparison, the normal Cu and Sn matrices next to the interfacial distortion zone exhibit a good atomic arrangement with few defects. The FFT