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Current induced segregation of intermetallic compounds in three-dimensional integrated circuit microbumps

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ABSTRACT

Electromigration will induce polarity effects on the formation and dissolution of intermetallic compounds (IMCs) at the electrodes in conventional solder joints. However, the entire solder joint of a microbump may convert to intermetallic compounds after prolonged current stressing. The present study investigated the growth behavior of intermetallic compounds in a 30 μm height Sn1.8Ag microbump plated on a Cu pillar with or without an intermediate Ni layer when the substrate metallization was either Organic Solderability Preservative-Cu (OSP-Cu) or Electroless Nickel/Electroless Palladium/Immersion Gold (ENEPIG). The progress of the growth of the intermetallic compounds under a current density of 1.0×10^4 A/cm^2 was investigated for up to 300 h. The segregation and growth of the intermetallic compounds revealed by a three-dimensional cross section during current stressing was observed and discussed.

1. Introduction

The need for miniaturization and multi-function performance in devices has led to the development of three-dimensional integrated circuit (3DIC) technology. A fine pitch die can be stacked in the z-direction using the through-silicon via (TSV) technique to interconnect with microbumps [1]. The development of 3DIC stacking technology has made it possible to minimize the pitch size between devices, enhance power efficiency, and enable higher packaging density. Solder plated on a Cu pillar is typically pure Sn or Sn-Ag, as restricted by the plating technology. A microbump is around 10–20 μm in diameter of which the volume is 1/100 to 1/1000 times that of a traditional 100 μm diameter flip chip solder bump [2,3].

The miniaturization of a solder bump significantly increases the current density passing through a joint, which leads to electromigration reliability concerns. The Blech product [4] implies that smaller joint heights tend to withstand greater current density without crack formation. However, intermetallic compound-related reactions may still lead to defects and failures in microbumps. In general, the failures induced by electromigration in solder bumps [5] may include the formation of voids or hillocks on the cathode/anode side due to the polarity effect, formation and propagation of cracks along the intermetallic compound/solder interface due to current crowding, or rapid dissolution of under bump metallization (UBM) to form IMCs, as driven by current flow.

The IMC transformation induced by current stressing causes the formation of voids between IMCs due to differences in molar volume [6]. Current stressing also induces dissolution and recrystallization of IMCs in the bulk of flip chip solder bumps [7,8]. The combination effect of electromigration and thermomigration causes aggregation of the Cu elements and eventual segregation of IMCs after recrystallization in a solder joint. The interactions between a solder and UBM due to polarized movement may eventually give rise to reliability concerns. The formation and growth behaviors of IMCs significantly determine the mechanical properties of solder joints. Fracture of various ball grid array (BGA) solder joints has shown failures occurring at the solder/IMC interface using the drop and impact test [9]. The crack may initiate and propagate in the solder region or along the interface depending on the composition and distribution of the solder and IMCs [9]. The

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distribution of IMCs is therefore influential on the reliability and the failure mechanism of microbumps. The present study investigated the three-dimensional growth behavior induced by current stressing of IMCs in Sn1.8Ag microbumps with various metallization structures. The progress of IMCs growth during current stressing was investigated and discussed.

2. Materials and methods

Fig. 1(a) shows the schematic configuration of the Sn1.8Ag microbumps investigated in the present study. A 30 μm thick Sn1.8Ag solder was electroplated on either Cu or Cu/Ni pillars (40 μm thick). The pillars were plated on the sputtered Ti/Cu metallization layers of an Si die. The Cu pad on the PCB substrate was either Organic Solderability Preservative-Cu (OSP-Cu) or a Cu pad with Electroless Nickel/Electroless Palladium/Immersion Gold (ENEPIG) metallization layers. After a 260 °C, 55s reflow process, Cu/Sn1.8Ag/OSP-Cu, CuNi/Sn1.8Ag/OSP-Cu, Cu/Sn1.8Ag/ENEPIG and CuNi/Sn1.8Ag/ENEPIG microbumps were produced. The dimensions of the die and substrate were, respectively, 9 mm × 9 mm × 0.78 mm and 27 mm × 27 mm × 1.8 mm. The silicon chip consisted of more than 2000 microbumps with a daisy chain for the electromigration investigation, as shown in Fig. 1(b). Microbumps A, C, D, G were stressed with a direct current (500 mA, 1.0×10^4 A/cm^2) in the direction indicated by the arrows at 125 °C under ambient conditions. The arrows from bottom to top (A, D) represent the electron flowing from the substrate towards the chip, and vice versa. In addition, joints B, E, and F are the microbumps with the current bypass used for the thermal benchmark. The IMC distribution in the electromigration test was investigated in the desired directions at various sub-cross sections by grinding, as shown in Fig. 1(c). The microbumps were ground to the maximum cross section to reveal the IMC location. Subsequently, the bumps were further ground to different sub-cross sections I, II, and III for investigating the IMCs in another direction. Field emission scanning electron microscope (FE-SEM) equipped with energy dispersive X-ray spectrometer (EDS) was used to evaluate the microstructural evolution and the intermetallic composition of the current stressed microbumps.

3. Results and discussion

3.1. The Cu/Sn1.8Ag/OSP-Cu microbump

Fig. 2(a) shows the microstructure of the as-reflowed Cu/Sn1.8Ag/OSP-Cu microbump. Scalloped Cu_6Sn_5 and layer Cu_3Sn were formed on both interfaces. Fig. 2(b) and (c) presents the maximum cross section of the microbumps after 200 h and 300 h of current stressing with a cathode substrate. The wavy morphology of the Cu cathode indicates Cu dissolution behavior. In this study, the thickness of the Cu pad was around 15 μm, as shown in Fig. 1(a). Rapid dissolution of Cu resulted in the consumption of the entire Cu pad after prolonged current stressing. This behavior was also found later for the cathodic Cu pad of CuNi/Sn1.8Ag/OSP-Cu. The rapid dissolution of Cu, as compared with the current bypass microbump shown in Fig. 2(f), triggered Cu_6Sn_5 to fully occupy the solder region after prolonged current stressing for 300 h, as shown in Fig. 2(c). There was still Cu pad remaining after 300 h of current stressing.

Fig. 2(d) and (e) show sub-cross sections I and II, corresponding to Fig. 2(b) and (c), of the Cu/Sn1.8Ag/OSP-Cu microbump under 1.0×10^4 A/cm^2 of current stressing for 200 h and 300 h. The remaining solder was found on the back side of the 200 h current stressed microbump at interface I and interface II, as indicated by the arrow. In the case of the prolonged current stressing of 300 h, although almost of the entire solder region was converted into Cu-Sn IMC, as indicated in Fig. 2(c), residual solder was also found on the back side of both interface I and interface II, as shown in

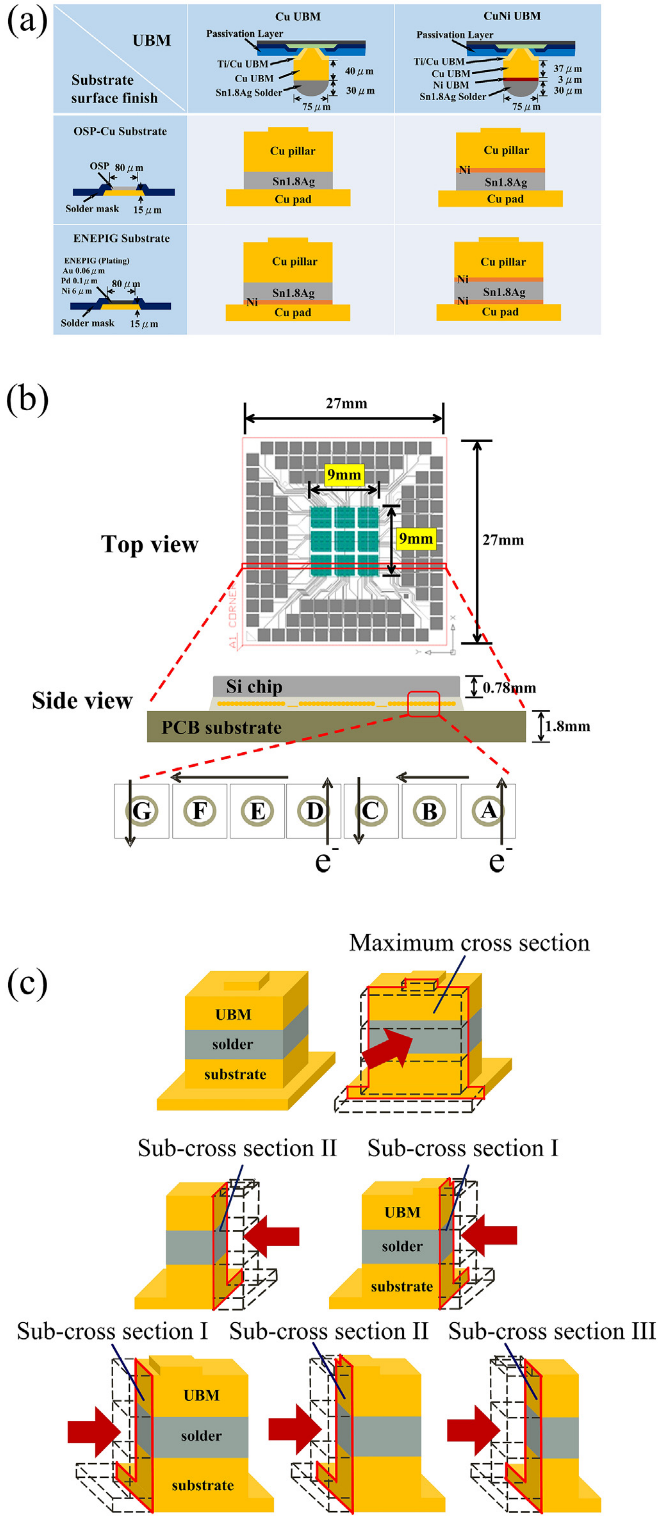

Fig. 1. Schematic configurations of Sn1.8Ag microbumps. (a) Structures of Cu/Sn1.8Ag/OSP-Cu, CuNi/Sn1.8Ag/OSP-Cu, Cu/Sn1.8Ag/ENEPIG and CuNi/Sn1.8Ag/ENEPIG microbumps; (b) The top and side views of the test vehicle and daisy chain in the current stressing investigation. Microbump A is the 5th microbump as counted from the right-hand side; (c) Observations with maximum and sub-cross sections. The sequential polishing of a sub-cross section indicated by the arrow shows different observations in Figs. 2 and 3 (the leftward polishing) and Figs. 4 and 5 (the rightward polishing).