

A Coupling between Electromigration(EM) and Kirkendall Effect in Sn-3.5Ag/Cu Solder Joint

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Abstract

Sn-3.5Ag/Cu solder joints were prepared by reflowing the eutectic solder on the PCB Cu opening which was electroplated using SPS additive in the bath. Effects of electromigration on the Kirkendall void growth were examined by applying electric current during isothermal aging at 150 °C, and analyzing SEM micrographs. Without current, Cu₃Sn and Cu₆Sn₅ intermetallic compounds (IMC) formed at the Sn-3.5Ag/Cu interface with a diffusion controlled mechanism. With electricity, (1×10^4 A/cm²), kinetics of Kirkendall void and IMC growth were affected, which depend on the direction of the electric current flow. At the anode side, IMC thickness, $\delta_{\text{Cu}_6\text{Sn}_5}$ increased remarkably, and the same was true of Kirkendall voids localized at the Cu₃Sn/Cu interface. On the other hand, $\delta_{\text{Cu}_3\text{Sn}}$ and $\delta_{\text{Cu}_6\text{Sn}_5}$ were both substantially suppressed at the cathode side. Cu₆Sn₅ showed a strong susceptibility to the polarity effect, while Cu₃Sn did not. Electromigration force induced additional tensile (or compressive) stress at the anode (or cathode), which accelerated (or decelerated) the void growth.

1. Introduction

With the demand for miniaturization of electronic devices current density of electronic components increases correspondingly, and electromigration of flip-chip solder joints under higher current density has recently emerged as a serious reliability concern for the high density flip-chip packaging [1-3]. Electromigration(EM) refers to migration of atoms in response to an applied electric field by the momentum transfer between moving electrons and diffusing atoms. In metallic interconnects, EM force induces matter flux toward the anode building compressive stress at the anode and tensile stress at the cathode. In the case of flip chip solder joints, EM can occur at much lower current density due to low critical product and the current crowding effect, which leads to subsequent void formation and phase separation [4]. Another consequence of electric current flow is Joule heating which develops nonuniform temperature distribution across the solder joint, thereby inducing thermomigration driven by the temperature gradients. Thermomigration is known to cause phase separation in the solder joints [5].

Another reliability concern in the flip chip solder joints is Kirkendall void formation. The original Kirkendall effect(KE) refers to movement of markers due to nonreciprocal diffusive flux of atoms of different species, and is known to induce tensile stress in the region of vacancy annihilation and compressive stress in the region of vacancy

generation [7,8,9]. Thus, voids found in the solder joint IMCs or their boundaries were often associated with the KE even though explicit mechanisms of void formation remained largely unknown. In Sn-3.5Ag/Cu solder joints, Yu and Kim [10] showed that the stress generated by KE was not sufficient to nucleate voids at the Cu₃Sn/Cu interface by itself, but could drive void nucleation and growth when the interface was embrittled by S. Since magnitude of the stress generated at the Cu₃Sn/Cu interface depends on the magnitude of the net matter flux, an application of EM force which induces additional matter flux is expected to change the local stress state and affect Kirkendall voiding.

Recently in Cu/Sn/Cu flip chip joints, Liu et al.[11] reported that localized Kirkendall voids formed only at the Cu₃Sn/Cu interface of the anode side and that voids did not form at the cathode side. In the present work, the coupling between EM and KE was investigated using Sn-3.5Ag/Cu joints. The same amount of S embrittlement was induced by adding constant amount of bis-sodium sulfopropyliddisulfide (SPS), a source of residual S in the Cu UBM, to the electroplating bath. Then, after the ageing treatment the void fractions at the Cu₃Sn/Cu interface were monitored from SEM micrographs of interrupted specimens with or without electricity application. Finally, the polarity effects on IMC growth and Kirkendall voiding were discussed along with the phase separation phenomenon.

2. Experimental procedure

A schematic diagram of the test vehicle used in the analysis is presented in Fig. 1 where Sn-3.5Ag/Cu solder joints were prepared by reflowing the eutectic solder balls with the diameter of $350\mu\text{m}$ over the Cu UBM ($20\mu\text{m}$ thick) for 1 minute at 260°C . The electroplating bath contained 1M $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, 0.7M H_2SO_4 and $3.0 \times 10^{-5}\text{M}$ SPS (bis-sodium sulfopropyl disulfide $\text{C}_6\text{H}_{12}\text{O}_6\text{S}_4\text{Na}_2$). In actual specimens, dummy solder balls were placed in arrays to make the solder ball height uniform, and the underfill between two PCBs helped to hold the solder ball mechanically. Subsequent ageing treatments were conducted at 150°C up to 400 hours with or without electric current flow. The electric current flow was kept constant at 4.15A which corresponded to the average current density of $1 \times 10^4 \text{ A/cm}^2$ over the pad area. Temperature of the solder joint was kept constant at 150°C by putting thermocouple near the corner of a solder ball contacting the bottom Cu UBM as shown in Fig.1(b). Thus, extra Joule heating effect caused by the current crowding was automatically taken care of, at least near the bottom PCB. Temperature at the upper PCB was expected to be slightly higher than that of the bottom PCB, but was not measured. Later, IMC thickness and Kirkendall voiding were measured from cross-sectional SEM micrographs shown in Fig.1(b) which were made out of the specimen Fig.1(a) by cutting along the y axis.

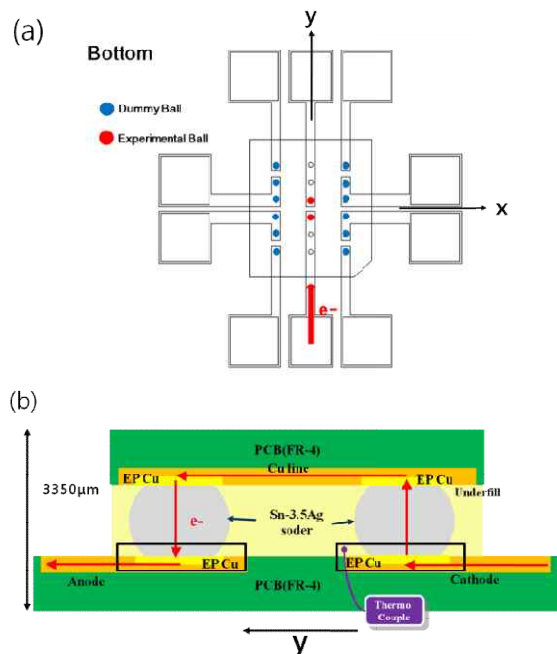


Fig.1. Schematic diagrams of specimens used for the electromigration studies; (a) top view and (b) cross-section of the center chip cut along the y axis intersecting the two solder balls at the center of (a). Interface microstructures near the bottom electrodes

(denoted as dotted boxes) were examined for the Kirkendall void fractions.

3. Results and discussion

3.1. Ageing without electric current flow

Microstructures of as-reflowed solder joint after a reflow of 1 minute at 260°C showed only scallop type Cu_6Sn_5 IMC at the Cu/Sn interface as shown in Fig. 2, and there were no Kirkendall voids at the solder joint interface.

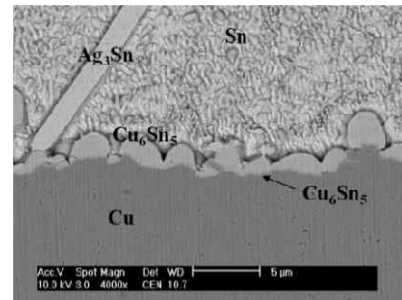


Fig.2. A cross-sectional back scattered electron (BSE) image of the as-reflowed solder joint without ageing treatment.

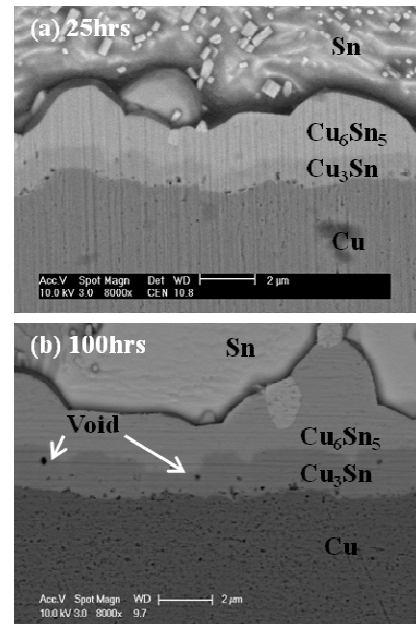


Fig.3. Cross-sectional BSE images of Sn-3.5Ag/Cu solder joint aged at 150°C for (a) 25 hrs and (b) 100 hrs without the current application.

With ageing at 150°C , without EM, initially scallop shaped Cu_6Sn_5 became flatter and formed layer structured IMCs; $\text{Cu}_3\text{Sn}/\text{Cu}_6\text{Sn}_5$ over the Cu UBM as shown in Fig. 3. Kirkendall voids formed only in Cu_3Sn and at the $\text{Cu}_3\text{Sn}/\text{Cu}$ interface, but no voids were found in Cu_6Sn_5 . With further ageing, void localization at the $\text{Cu}_3\text{Sn}/\text{Cu}$ interface became

more apparent. It was shown previously [7] that voids nucleated by embrittlement of $\text{Cu}_3\text{Sn}/\text{Cu}$ interface by interfacial segregation of residual S coming from SPS and the presence of residual stress inherent in the electroplating process and that voids grew by the local tensile stress arising from the nonreciprocal diffusion of Cu and Sn atoms across the $\text{Cu}_3\text{Sn}/\text{Cu}$ interface. Both Cu_3Sn and Cu_6Sn_5 thickened parabolically with time suggesting that the dominant mechanism of IMC growth was diffusion-controlled layer growth by Kidson[12] rather than interfacial reaction controlled growth.

3.2. Ageing under the electric current density of $1 \times 10^4 \text{ A/cm}^2$

When the electricity was applied to the solder joints during the ageing treatment, kinetics of IMC thickening were affected by the additional matter flow driven by the EM force, which varied with the current density and the polarity [6]. As shown in Fig. 4, Cu pad consumption and IMC thickening varied markedly with polarity, and it can be seen that the Cu pad was gradually consumed by EM at the cathode side, while Cu_6Sn_5 phase thickened at the anode side by diffusion of Cu atoms from cathode. It is interesting to note that diffusing Cu atoms formed islands of Cu_6Sn_5 precipitates in the solder matrix, which drifted toward anode by the current flow. As Cu_6Sn_5 precipitates reached the anode, they formed a thick layer of Cu_6Sn_5 IMC over the Cu_3Sn as shown in Fig. 4(b)

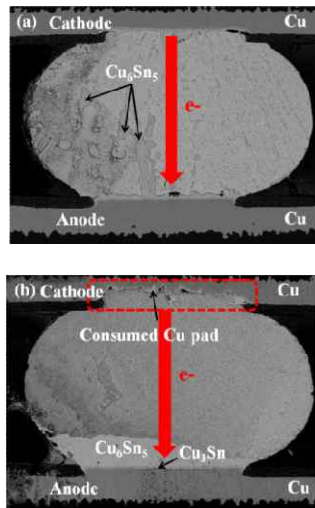


Fig.4. Cross-sectional BSE images of Sn-3.5Ag/Cu joints aged at 150°C under the electric current density of $1 \times 10^4 \text{ A/cm}^2$ after (a) 100 hrs and (b) 200 hrs, respectively.

Positions of the Cu UBM at the bottom PCB before the reflow were taken as the reference, and variations of interface positions; $\text{Cu}/\text{Cu}_3\text{Sn}$, $\text{Cu}_3\text{Sn}/\text{Cu}_6\text{Sn}_5$ and $\text{Cu}_6\text{Sn}_5/\text{Sn}$ are presented as

functions of ageing time in Fig. 5. Negative positions in the figure correspond to consumption of Cu UBM. Thus, the Cu consumption was the most severe at the cathode side. From positions of various interfaces, thicknesses of Cu_3Sn and Cu_6Sn_5 can be deduced straightforwardly, and are presented in Fig.6. Note that only Cu_6Sn_5 thickening was affected by EM; being accelerated at the anode side, but slightly decelerated at the cathode side. In contrast, effect of EM on the Cu_3Sn thickening was rather marginal.

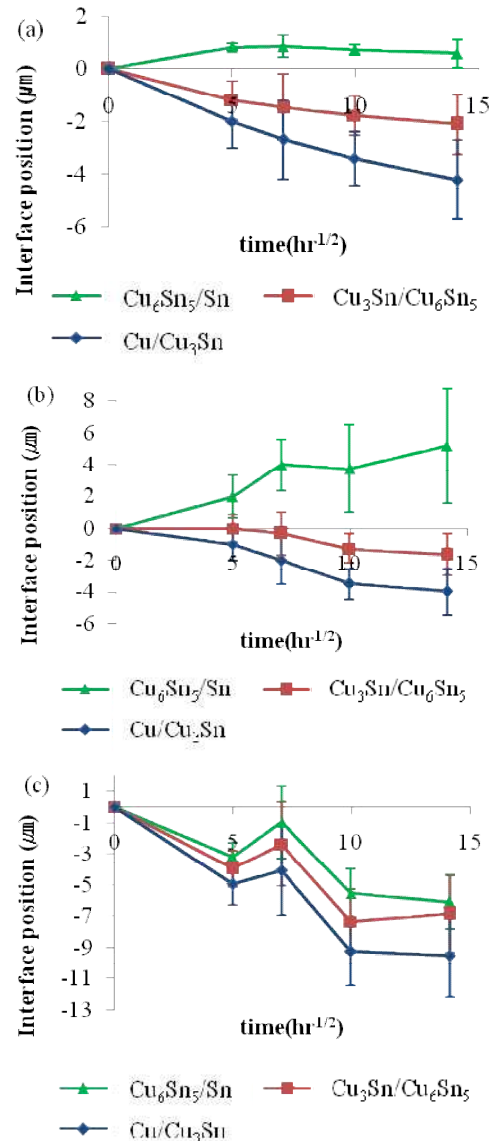


Fig.5. Variations of interface positions as functions of ageing time at 150°C ; (a) without current, (b) anodic and (c) cathodic conditions.

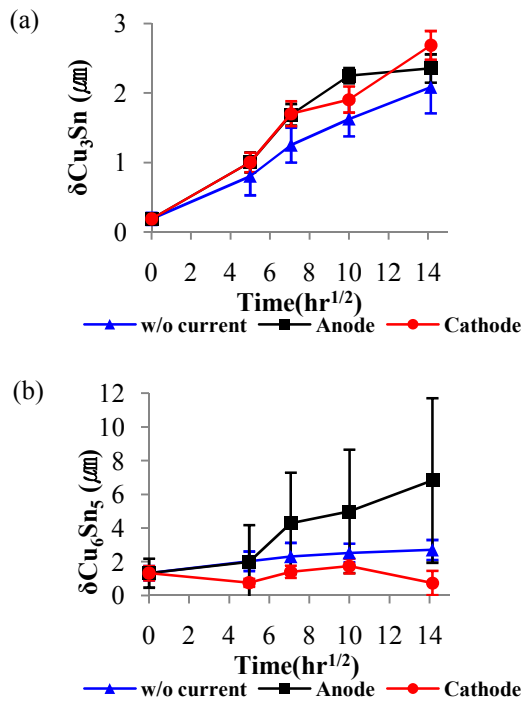


Fig.6. Thickness of IMCs deduced from Fig. 5 for the three cases. (a) Cu_3Sn (b) Cu_6Sn_5 .

Cross-sectional SEM micrographs of the solder joint aged under the electric current density of $1 \times 10^4 \text{ A/cm}^2$ were presented in Fig.7 where the direction of the electron flow is indicated with an arrow. As noted, Cu_6Sn_5 IMC thickening was affected by EM polarity effect but Cu_3Sn IMC thickening was not, even though it was slightly higher than that of the case without current application. This is basically consistent with the report by Gan and Tu[6] on Sn-3.5Ag-0.7Cu/Cu joints.

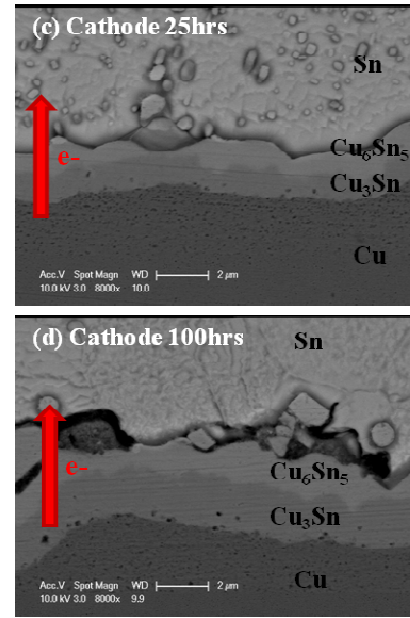
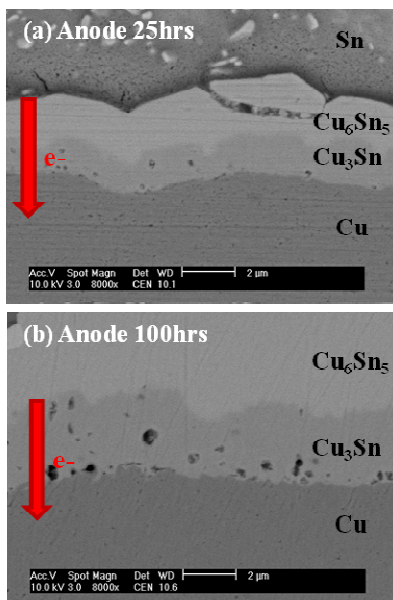


Fig.7. Cross-sectional BSE images of Sn-3.5Ag/Cu joints aged at 150°C under the electric current density of $1 \times 10^4 \text{ A/cm}^2$; (a) and (b) at anode side, (c) and (d) at cathode side after 25 and 100 hrs, respectively. SEM micrographs from the solder/Cu UBM interfaces at the bottom PCB (anode micrographs from the left solder and cathode micrographs from the right solder ball).

3.3 Kirkendall voiding

As shown in Fig.7, Kirkendall voids were more numerous at the anode than at the cathode. The fraction of Kirkendall voids at the $\text{Cu}_3\text{Sn}/\text{Cu}$ interface was measured over SEM micrographs and presented in Fig.8. Note that localized Kirkendall void formation at the $\text{Cu}_3\text{Sn}/\text{Cu}$ interface was enhanced at the anode, but detracted at the cathode side by EM. Interfacial void fraction was largest and increased with the ageing time at the anode, but seemed to saturate at the cathode after 25 hours. This is consistent with the report by Liu et al [11] which showed that EM caused the polarity effect not only on IMC thickening but also on Kirkendall void growth in Sn/Cu solder joint. There being no externally applied stress, this is an indication of the fact that EM imposes an additional tensile stress at the anode but compressive stress at the cathode. A parallel work on the tensile stress driving the Kirkendall void growth estimated the magnitude of tensile stress at the anode, cathode and without current to be ~ 24.5 , ~ 1.5 and $\sim 14 \text{ MPa}$, respectively [13]. Thus, EM appears to approximately $\sim 10 \text{ MPa}$ of tensile (compressive) stress additionally at anode (cathode).

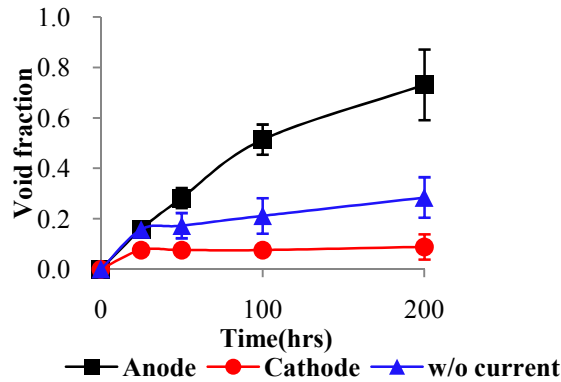


Fig.8. The fraction of Kirkendall voids at Cu/Cu₃Sn interface as a function of ageing time at 150°C under anodic, cathodic and w/o current conditions.

4. Conclusions

Preferential Kirkendall void nucleation at the Cu₃Sn/Cu interface was induced by adding a constant amount of SPS to the electroplating bath of Cu which was a main source of S segregation at the interface. Application of the electric current showed the polarity the effect in IMC thickening and Kirkendall void growth in a different way. Cu₆Sn₅ showed strong polarity effect while Cu₃Sn did not. Both Cu₆Sn₅ thickening and Kirkendall void growth at the Cu₃Sn/Cu interface were enhanced at the anode but suppressed at the cathode. Magnitude of stress imposed locally at electrodes was estimated to be ~10MPa (tensile stress at the anode and compressive stress at cathode).

Acknowledgements

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