# Effects of Electromigration(EM) on the Kirkendall Void Formation in Sn-3.5Ag/Cu Solder Joints

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Key words: Sn-3.5Ag solder joint, Electromigration, Kirkendall void, polarity effect

**Abstract**

*Kirkendall voids and the micro voids induced by electromigration result in the serious failure in the solder interconnect. Interfacial reactions between Sn-3.5Ag solder and the electroplated Cu using SPS additive in the bath were investigated under high current condition. During subsequent isothermal aging at 150°C, the formation of Kirkendall voids was accelerated by S segregation at the void surface and Cu/$Cu_3Sn$ interface, and then the voids were preferentially localized at the interface. And under high current flow ($1X10^4 A/cm^2$) at the cathode side, electromigration caused the micro voids at the $Cu_6Sn_5$/Sn interface. The growth of Kirkendall voids and the micro voids were both affected by aging time and current density. Effects of current flow on the growth of Kirkendall voids and the micro voids were examined by applying high electric current during isothermal aging at 150°C. From the measurements of the fraction of voids at the Cu/$Cu_3Sn$ and $Cu_6Sn_5$/Sn interfaces on SEM micrographs and analysis of the kinetics of void growth, which voids are more dominant was examined according to the time and the current density. Furthermore, under current flow the intermetallic compounds (IMC) thickening as well as voids growth was affected by polarity. Even though Cu was consumed remarkably, the growth of both $Cu_3Sn$ and $Cu_6Sn_5$ IMCs was suppressed at the cathode side. On the other hands, the thickness of $Cu_6Sn_5$ at the anode side was increased by reaction with Cu flux atoms which migrate towards the anode from the cathode Cu line.*

## 1. Introduction

As the electric devices need to be more functional and miniaturized, the electrical interconnection input/output counts are increased and the bump size will be smaller significantly. The electromigration reliability concerns have emerged from the higher current density application on the flip chip solder joint [1-3]. Electromigration-induced open circuit failure caused by voids and hillock formation in the metal interconnection has been reported frequently. Also, high electric current flow causes current crowding and Joule heating which develop nonuniform current and temperature distribution across the solder joint. The temperature gradients can induce the thermomigration which is known to cause phase separation in the solder joints [4-5]. Another reliability issues on the electromigration is the polarity effect on the flip chip solder joint. In the Sn-3.8Ag-0.7Cu flip-chip solder joint, Gan and Tu[6] investigated the EM-induced polarity effect on the IMC thickening and the void growth. In Cu/Sn/Cu flip chip joints, Liu et al.[7-9] reported that EM-enhanced Kirkendall voids formed only at the Cu/$Cu_3Sn$ interface of the anode side and that voids were not formed at the cathode side. And they also reported micro-scale voids at the $Cu_6Sn_5$/Sn solder interface of the cathode side. On the contrary, Chao et al. [10-12] reported that Kirkendall voids were formed at the Cu/$Cu_3Sn$ interface of the cathode side in Cu/Sn-3.5Ag flip chip solder joint. The Kirkendall voiding was caused by nonreciprocal diffusive flux of atoms of different species. Yu and Kim [13] showed that the S segregation at the Cu/$Cu_3Sn$ interface enhanced to nucleate voids at the interface in Sn-3.5Ag/Cu solder joints. And vacancy annihilation at Cu/$Cu_3Sn$ interface can induce tensile stress which increases the Kirkendall void growth. On the other hands, vacancy generation can induce compressive stress [14-16]

In the present work, the EM induced Kirkendall void growth was investigated using Sn-3.5Ag/Cu joints. Additional matter flux induced by electromigration is expected to change the local stress state at the interfaces between Cu UBM and solder (includes Cu/$Cu_3Sn$, $Cu_6Sn_5$/Sn and so on.) and affect Kirkendall void growth at each interface. The constant amount of bis-sodium sulfopropyl disulfide (SPS) was added to the Cu electroplating bath to induce the same amount of S segregation at the Cu/$Cu_3Sn$ interface during isothermal aging treatment. Then high electric current was applied to the flip-chip solder joint, which was maintained at 150°C. Finally, the polarity effects on IMC growth and Kirkendall voiding were discussed by measuring IMC thickness and the void fractions at the $Cu/Cu_3Sn$ and $Cu_6Sn_5/Sn$ interface from SEM micrographs.

## 2. Experimental procedure

A schematic diagram of the test sample was presented in Fig.1. At first, PCB Cu openings are chemically etched using commercial Cu etchant to get the electroplated Cu height to be lower than the solder mask. The 20㎛ thick Cu UBM was electroplating using the electroplating bath contained 1M $CuSO_4{\cdot}5H_2O$, 0.7M $H_2SO_4$ and $3.0\times10^{-5}$M SPS (bis-sodium sulfopropyldisulfide $C_6H_{12}O_6S_4Na_2$). To make a Sn-3.5Ag/Cu solder joints, reflow process was conducted for 1 minute at 260°C using Sn-3.5Ag solder ball with the diameter of 350㎛. Experimental temperature was kept constantly at 150°C measuring with K-type thermocouple which was fixed near by the corner of the solder ball. And then underfill was filled in the gap between the upper and substrate PCBs to maintain the solder ball shape. The dummy solder balls were placed in arrays to make the solder ball height uniform and to get mechanical support. Subsequent ageing treatment was conducted at 150°C up to 400 hrs with or without electric current flow. The electric current was applied constantly at 4.15A which corresponded to the average current density of $1\times10^4$ A/cm$^2$ over the pad opening area.

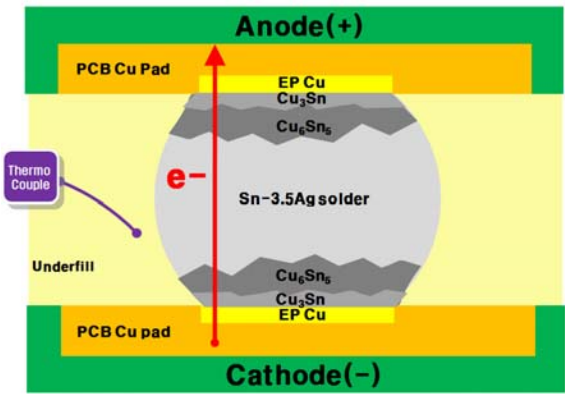


**Fig.1.** Schematic diagrams of specimen used for the electromigration study.

## 3. Results and discussion

### 3.1. Aging without electric current flow

The reflow process was performed at 260°C for 1 minute to make an electrical interconnection between the two PCB pads using a solder joint. As shown in Fig. 2, only scallop type $Cu_6Sn_5$ IMC and very thin $Cu_3Sn$ IMC are observed at the Cu/Sn interface, and Kirkendall voids were not formed between the Cu and IMCs interface.

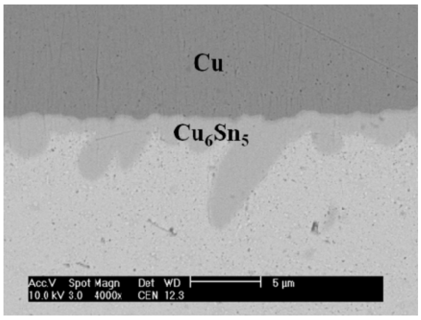


**Fig.2.** A cross-sectional back scattered electron (BSE) image of the as-reflowed solder joint without aging treatment.

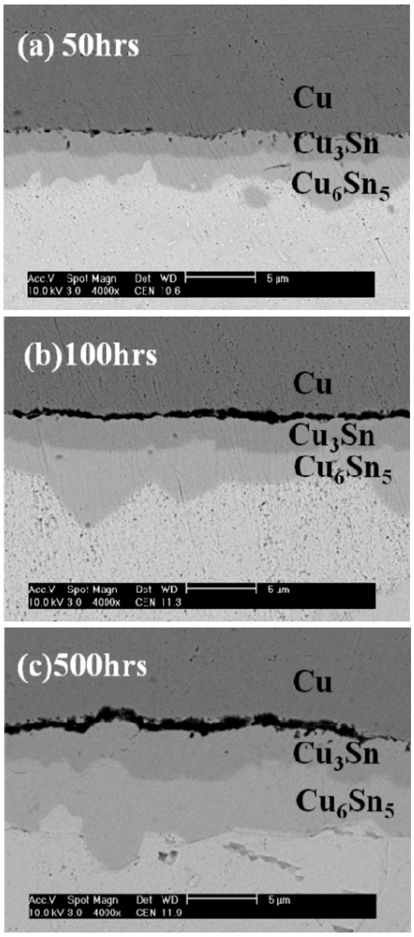


**Fig.3.** Cross-sectional BSE images of Sn-3.5Ag/Cu solder joint aged at 150°C for (a) 50 hrs and (b) 100 hrs (c) 500hrs without the current application.

Without current application, the samples were aged at 150°C subsequently, scallop type $Cu_6Sn_5$ became more flat and formed layer structured IMCs; two IMCs, $Cu_3Sn$ and $Cu_6Sn_5$ over the Cu UBM grew according to the aging time as shown in Fig. 3. At the first time, Kirkendall voids formed in $Cu_3Sn$ layer and at the $Cu/Cu_3Sn$ interface, but no voids were observed in $Cu_6Sn_5$ layer and at the $Cu_6Sn_5/Sn$ interface. With further aging treatment, voids were predominantly distributed at the Cu/$Cu_3Sn$ interface. As shown in Fig.4, Both $Cu_3Sn$ and $Cu_6Sn_5$ IMCs were thickened parabolically with time. It shows that the dominant mechanism of IMC growth was diffusion-controlled layer growth by Kidson[17] rather than interfacial reaction controlled growth. $Cu_6Sn_5$ IMC growth is more affected by the diffusion process than $Cu_3Sn$. $Cu_3Sn$ growth is rather slower than the $Cu_6Sn_5$ growth and it looked to be convergent to the stable thickness.

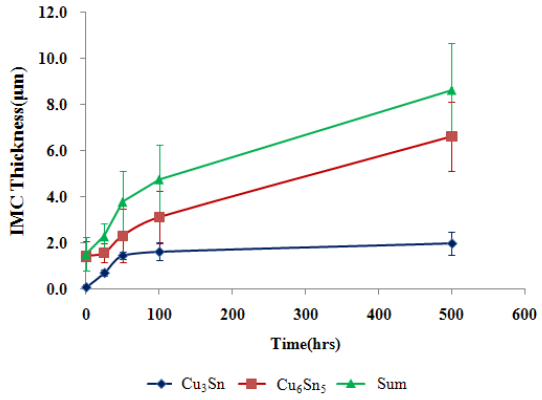


**Fig.4.** IMC thickening at 150°C without the current

### 3.2. Aging under the electric current density of 1x10$^4$ A/cm$^2$

The electrical current application to the solder joints with simultaneously aging treatment at 150°C affected IMC thickening by the additional matter flow driven by the EM force, which varied with the polarity.

Cross-sectional SEM micrographs of the solder joint at the anode side and at the cathode side aged under the electric current density of 1×10$^4$ A/cm$^2$ were presented in Fig 5 and Fig 6, respectively. The direction of the electron flow is indicated with an arrow. The variation of the IMC thickness was presented under current was plotted in Fig 7. Note that only $Cu_6Sn_5$ thickening was affected by EM; being accelerated at the anode side, but decelerated at the cathode side. On the contrary, effect of EM on the $Cu_3Sn$ thickening was rather marginal. $Cu_6Sn_5$ IMC thickening was apparently affected by EM polarity effect, but $Cu_3Sn$ IMC thickening was not. It was slightly higher than that without current application. This is basically consistent with the report by Gan and Tu[6] on Sn-3.5Ag-0.7Cu/Cu joints.

Liu et al.[7] investigated that variation of the IMC thickness was measured under EM test at different elevated temperatures; 155°C, 180°C, and 200°C under the current density of 5.3x10$^3$A/cm$^2$. At anode side, total thickness of the IMCs increased linearly with the time. At the cathode side, the Cu UBM consumed proportional to the current stressing time.

Chao et al.[10] reported that on the damage formation in the Sn-3.5Ag solder joint on the Cu UBM under the high current states. When the two different electric current densities of 4.12x10$^4$A/cm$^2$ and 5.16x10$^4$A/cm$^2$ were applied to the joint at 150°C (constant temperature to the actual solder joint concerned with Joule heating), two interfacial IMCs including $Cu_3Sn$ and $Cu_6Sn_5$ were grown proportionally to the time at the anode side. Compared to the aging samples, the growth of $Cu_6Sn_5$ was more affected by the current. Respectively, the thickening of $Cu_3Sn$ was rather suppressed than that in the case of only aged specimen. In both studies, when solder joint were only annealed at each experimental temperature conditions, the Cu consumption at the interface and the thickening of both $Cu_6Sn_5$ and $Cu_3Sn$ were parabolically increased with time.

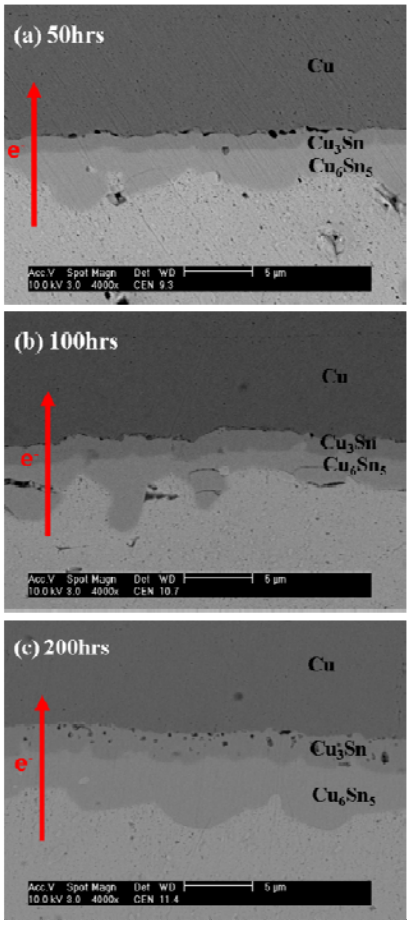


**Fig.5.** Cross-sectional BSE images of Sn-3.5Ag/Cu joints aged at 150°C under the electric current density of 1×10$^4$ A/cm$^2$ at anode side, after (a)50hrs, (b)100hrs, and (c)200hrs, respectively.

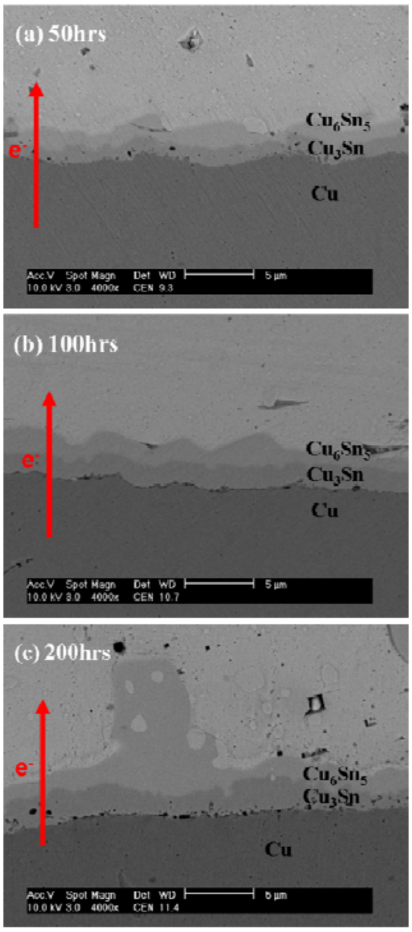


**Fig.6.** Cross-sectional BSE images of Sn-3.5Ag/Cu joints aged at 150°C under the electric current density of $1\times10^4$ A/cm$^2$ at cathode side, after (a)50hrs, (b)100hrs, and (c)200hrs, respectively.

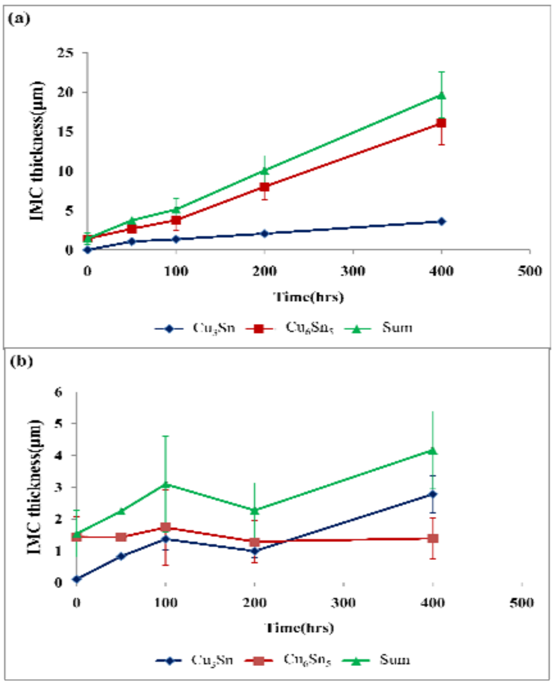


**Fig.7.** IMCs thickening with the current; (a) at anode side and (b) at cathode side, respectively.

### 3.3 Kirkendall voiding and microvoiding

As shown in Fig.5 and 6, Kirkendall voids at the Cu/$Cu_3Sn$ interface were more numerous at the cathode than the anode side. Note that localized Kirkendall void formation at the Cu/$Cu_3Sn$ interface was accelerated at the cathode, but decelerated at the anode side by EM. Interfacial void fraction was increased with the aging time at the cathode. The micro voiding which induced by electromigration between $Cu_6Sn_5$ and Sn-based solder interface at cathode side was presented in Fig.8. The Kirkendall void growth at Cu/$Cu_3Sn$ interface was also observed as shown in Fig.8.

In the study of Gan and Tu [6], voids at the $Cu_6Sn_5$/Sn solder interface were observed at the cathode side after 87hrs aged at 180°C in the condition of the current density of 3.2x10$^4$A/cm$^2$. And the void at the Cu/$Cu_3Sn$ interface was also formed in the same experimental conditions. Chao and Chae et al. [10-12] reported that the Kirkendall void formation occurred at the Cu/$Cu_3Sn$ interface with the solder reflow and the aging treatment only at 150°C for 263hrs. And when a significant current applied in the magnitude of 5.16x10$^4$A/cm$^2$ on the solder joint with a prolonged aging over 300hrs, EM-enhanced crack was propagated at the cathode $Cu_3Sn$/$Cu_6Sn_5$ interface and in the $Cu_6Sn_5$ layer. Finally, electomigration damaged to the cathode side of solder joint and made a serious open failure. Liu et al. [9] also mentioned the void formation at the $Cu_6Sn_5$/Sn solder interface of the cathode, which were occurred by electromigration under the current density of 5.3x10$^3$A/cm$^2$ at 55°C after 250hrs. And at the anode Cu/$Cu_3Sn$ interface, EM-enhanced Kirkendall voids coalesced near the current-exit corner. They reported that the different current stress density distribution at the solder joint interface resulted in various EM-induced failures according to the polarity. At the cathode joint interface away from the current-entry point, void formation at the $Cu_6Sn_5$/Sn interface was accelerated by electromigration in the lower current density condition of 1.0x10$^4$A/cm$^2$ than the current-entry point. And the difference of the current density and thermal stress were suggested as main causes of the extensive EM-enhanced Kirkendall void at the anode Cu/$Cu_3Sn$ interface. But any obvious reason of the Kirkendall void formation at the Cu/$Cu_3Sn$ interface of the anode was not mentioned.

In the previous work [18], the void formation tendency at the Cu/$Cu_3Sn$ interface shows that void are more numerous at the anode than cathode side. This result showed opposite tendency compared with the present work. The IMCs thickening is clearly different from the diffusion-controlled growth. But it is not linear to the time, but rather similar to the parabolic growth with time. Some studies including Liu, Chao and the present work showed that the growth tendency of IMCs was linear with time when the solder joint were more affected by EM. And it is possible that additional thermal stress from nonuniform current density distribution near the current exit-point affected the Kirkendall void formation at the Cu/$Cu_3Sn$ interface of the anode in the previous results.

The main cause of the Kirkendall void formation at Cu/$Cu_3Sn$ interface came from the S segregation which was absorbed from the SPS additives during the Cu electroplating process. When vacancies are annihilated at the Cu/$Cu_3Sn$ interface can induce tensile stress. At the interface which was embritted by S, the voids can grow by local tensile stress, originating from residual stress in the film and/or the Kirkendall effect. After 200hrs, the magnitude of the Kirkendall void at Cu/$Cu_3Sn$ was passed over the magnitude in the case of the isothermal conditions. Compared to Kirkendall voiding at Cu/$Cu_3Sn$, micro voiding at $Cu_6Sn_5$/Sn-3.5Ag solder interface at the cathode side is larger and may cause severe damage to the reliability to the solder joint. This micro voiding was shown only at the cathode side. The high applied current may caused the voiding failure at the solder/IMC interface.

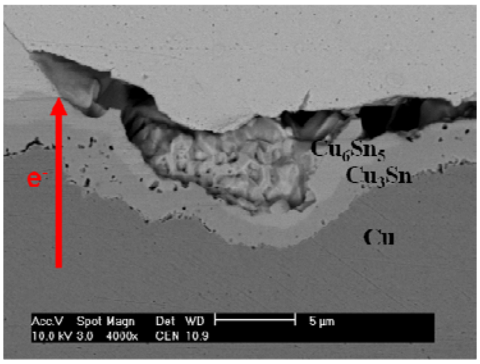


**Fig.8.** Miro voids at the $Cu_6Sn_5$/solder interface and the Kirkendall void at the Cu/$Cu_3Sn$ interface, aged at 150°C under the electric current density of $1\times10^4$ A/$cm^2$ at cathode side after 100hrs.

## 4. Conclusions

Kirkendall voids were preferentially distributed at the Cu/$Cu_3Sn$ interface in Sn-3.5Ag/Cu solder joint. Main cause of the localized void was S segregation at the interface by adding a constant amount of SPS to the electroplating bath of Cu. When electrical current were applied to the solder joint, the IMC thickening and Kirkendall void growth were showed differently according to the polarity. $Cu_6Sn_5$ thickening showed strong polarity effect while $Cu_3Sn$ did not. Both $Cu_6Sn_5$ and $Cu_3Sn$ thickening were accelerated at the anode, but Kirkendall void growth at the Cu/$Cu_3Sn$ interface was suppressed. Otherwise, at the cathode, $Cu_6Sn_5$ thickening was decelerated, but $Cu_3Sn$ thickening was almost same compared to the anode and isothermal conditions. And Kirkendall void growth at the Cu/$Cu_3Sn$ interface was larger than that at anode side. Micro voids between the Sn-3.5Ag solder and $Cu_6Sn_5$ were apparently affected by the current flow. These voids were observed only at the cathode side.

## Acknowledgements

This work was supported by a National Research Foundation of Korea (NRF) under the grant MEST No.2010-0000862.

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