

IMC Growth Mechanisms of SAC305 Lead-Free Solder on Different Surface Finishes and Their Effects on Solder Joint Reliability of FCBGA Packages at Different Thermal Aging and Temperature Cycle Conditions

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Abstract

Intermetallic Compound (IMC) growth behavior of lead-free solder plays an important role in Ball Grid Array (BGA) solder joint reliability for Flip Chip BGA (FCBGA) packaging application. Growth mechanism of IMC is reported based on diffusion model and thermal treatment such as Accelerated Thermal Cycling (ATC) and isothermal aging exposure also contributes growth rate and morphology of lead-free solder IMC. Among the lead-free solder alloys, Sn-3.0wt.%Ag-0.5wt.%Cu (SAC305) solder is a promising substitute for Sn-Pb because of its good mechanical properties and wettability with current surface finishes. After thermal exposure, BGA solder joint reliability is degraded due to IMC formation and its growth. In this study, two different thermal treatments, ATC and isothermal aging, and two different pad surface finishes, Solder on Pad (SOP) and Electroless Ni Immersion Gold (ENIG), are considered in terms of IMC growth rate and its mechanical solder joint reliability. SOP finished interface forms thin ϵ -phase Cu_3Sn layer and scallop-like η -phase Cu_6Sn_5 layer, in contrast, ENIG finished interface forms thick $(\text{Cu},\text{Ni})_6\text{Sn}_5$ IMC layer and it prevents overall IMC growth. Different surface finished test vehicles are evaluated in ATC test at 0°C to 100°C temperature range and Ni diffusion layer shows longer solder joint fatigue lifetime than non-diffusion barrier interface based on micro cross-section and dye penetration analysis results. In isothermal aging test at 100°C and 150°C , aging temperature and time are valid factors to decide mechanical shock reliability. Interfacial fractures are found at 100°C aged test vehicle due to easier crack propagation at interface between thin Cu_3Sn layer and scallop-like Cu_6Sn_5 layer based on SEM microstructure analysis results. Finally, this investigation proposes how to improve solder joint reliability and prevent interfacial fracture for SAC305 lead-free application.

Keyword: intermetallic compound, SAC305, FCBGA, solder joint fatigue, Cu_6Sn_5 , Cu_3Sn , $(\text{Cu},\text{Ni})_6\text{Sn}_5$.

1. Introduction

In the past, lead-containing solders had been widely used in the electronic industry. Nevertheless, because of the toxic effect of Pb on human beings, the electronic industry has been forced to develop an alternative lead-free solders solution and investigate to replace Sn-Pb eutectic solders. Although many of the processing problems have been solved for lead-free solders, the comprehensive understanding of long-term reliability of solder joints still remains a challenge [1]-[2]. With the miniaturization of electronic components, more I/O counts are needed in the same area, resulting in the pitch and joint size of solder joints are becoming ever smaller. This is an increasing challenge for the long-term reliability of solder joints. In order to make sure the components can perform well during their lifetime, the study of the property determination of solder joint is worthwhile.

Many different solders were found to be suitable as substitutes for the standard Sn-Pb solders. The most favored lead-free solders fall into two general alloy families, namely, the so-called Sn-Ag group and the so-called Sn-Ag-Cu (SAC) group. These solders have the advantage of good processability and high reliability of the solder joints produced [1]-[2]. Among lead-free solders, SAC solder alloy is widely used due to its relatively low melting point, favorable thermo mechanical fatigue resistance in most thermal cycle testing, and cost consideration [3]. Most of SAC solder alloys contain more than 90wt.% of Sn. The ternary reaction is reported as a decomposition of the melt liquid into three phases, Ag_3Sn , Cu_6Sn_5 , and Sn at around 216.8°C . The eutectic composition was determined to be 93.6wt.%Sn-4.7wt.%Ag-1.7wt.%Cu [1].

2. Diffusion Model for IMC Growth and Surface Finish Effect

The diffusion control model is based on diffusion through intermetallic layers and the initial condition of the growth model is the point where a continuous IMC is established. Once a continuous layer is established, additional growth requires diffusion of the reaction species through the IMC layer. The grain structure of the IMC layer has a key influence on diffusion rate through the layer [4].

Shaefer *et al.* reported the typical morphology for the IMCs of Sn-Cu system is planar ε -phase Cu_3Sn near Cu substrate and scallop-like η -phase Cu_6Sn_5 near solder. The η -phase is the majority component, grows more rapidly, and appears first during the initial states of growth. It is assumed that each scallop of the η -phase layer corresponds to one grain. η -phase grains are assumed to have a hexagonal shaped base toward the Cu substrate and a rounded top, spherical or parabolic, in contact with the liquid solder [4]. By applying one dimensional approximation, the flux across the η -phase layer is given by Fick's first law. The growth rate is usually controlled by the diffusion of the faster diffusing species. The total flux through the η -phase layer is the sum of the volume diffusion and grain boundary contributions. The flux resulting from volume diffusion may be obtained by applying Fick's law and hexagonal shaped scalloped grains for grain boundary diffusion. For the η -phase IMC layer is dominated by the grain boundary diffusion to transport through the IMC and the total flux is approximately equal to the grain boundary flux alone.

$$X_{Ave} \approx -\{D_{\eta}^{GB} V_{IMC} (\frac{\delta \Delta C}{\sqrt{3}k})\}^{\frac{1}{3}} t^{\frac{1}{3}} \text{-----Eqn(1)}$$

where, X_{Ave} is average layer thickness, D_{η}^{GB} is the grain boundary diffusion coefficient of η -phase, V_{IMC} is volume of IMC, δ is grain boundary width, $k = X_{AveGB} / X_{Ave}$, and t is time. The IMC layer growth which is limited by the grain boundary diffusion, in a system where the grains coarsen in production to the layer thickness, the layer thickness will follow a $t^{1/3}$ dependence on time [4]-[5].

Generally, the SAC lead-free solder on Cu substrate shows Cu_6Sn_5 IMC growth as a function of time of reflow or annealing as shown in the equation (1). Fix *et al.* reported that the scallop-like Cu_6Sn_5 was observed in the as-reflowed solder joint without planar Cu_3Sn in the case of Sn-4.0wt.%Ag-0.5wt.%Cu (SAC405)/Cu interface. A Cu_3Sn is not observed after certain level of aging due to its higher

activation energy [1]. For thickening of η -phase IMC and ε -phase IMC in liquid Sn-Cu reaction, their activation energies are reported as 13.4kJ/mol and 29.2kJ/mol, respectively [6].

According to published reports, Zribi *et al.* reported that the average growth rate of the $(\text{Cu},\text{Ni})_6\text{Sn}_5$ layer was higher than that of Ni_3Sn_4 in Sn/Ni interface after certain time of annealing. This observation is consistent with the above grain boundary diffusion controlled model that the layer thickness will follow a $t^{1/3}$ dependence on the reflow time and thickness of the Cu_6Sn_5 and $(\text{Cu},\text{Ni})_6\text{Sn}_5$ IMC layers show a parabolic shape trend [7]. Choi *et al.* noted that the IMC composition corresponding to $(\text{Cu},\text{Ni})_6\text{Sn}_5$ is found to have formed after reflow. Apparently, the Ni atoms substituted for some of the Cu atoms in the Cu_6Sn_5 phase in the case of SAC305/ENIG interface [8]. Ho *et al.* also reported that the $(\text{Ni}_{1-x}\text{Cu}_x)_3\text{Sn}_4$ layer becomes a very thin $(\text{Cu}_{1-y}\text{Ni}_y)_6\text{Sn}_5$ layer during solidification when Cu concentration increases to 0.5wt.% [9]. The growth rates of Cu_6Sn_5 and $(\text{Cu},\text{Ni})_6\text{Sn}_5$ are compared to each other in the following section.

3. Lead-free Solder Joint Integrity Experiment

3.1 ATC test for IMC Growth

In the BGA solder joint fatigue lifetime experiment with the SAC305 lead-free solder, two different surface finishes, SOP and ENIG, were considered. The ATC test condition was set to comply with IPC-9701 standard (0°C to 100°C temperature cycle, 10°C/min ramp up and cool down rate, 10 min dwell time at 0°C and 100°C). In-situ event detectors monitored the continuity of the daisy chains on the test vehicle. The daisy chain connections were continuously monitored by the event detector with the resolution of 0.2 μsec . When the resistance of the daisy chain net exceeded 1000 Ohms, the computer would record the signal from event detector and flag as one event [10]. The cycle to failure was defined as the number of thermal cycles occurred at the first verified event.

Table 1. ATC test vehicle information.

PKG type	2209pin FCBGA	PKG body	50x50mm ² 1mm pitch
ASIC die	17.3x17.3mm ²	PKG structure	2pc Cu heat spreader
Substrate	2/4/2 build up (1.1mm)	Pad structure	SMD SOP finish
FC solder	SAC305	BGA solder	SAC305
Test board	10.6x7.9inch ² (14 layer) Lead-free mat'l	Board pad structure	NSMD OSP finish

The test vehicle employed a 1.0mm pitch FCBGA on Bismaleimide Triazine (BT) resin substrate. The test package had 2209 I/O with a body size of 50 x 50 mm². The BT substrate was made with 8 metal layers with a thickness of 1.1mm. Table 1 demonstrates the test vehicle information. After completing the ATC 10,000 cycles, two different surface finished samples clearly show different solder joint fatigue lifetimes and its Weibull plot in Table 2 and Figure 1, respectively.

Table 2. ATC evaluation result.

Lot	1 st fatigue failure	N(63.2%)
SOP 197mil	~7,875 cycles	11,811 cycles
ENIG 197mil	No fatigue failure up to 10,823 cycles	

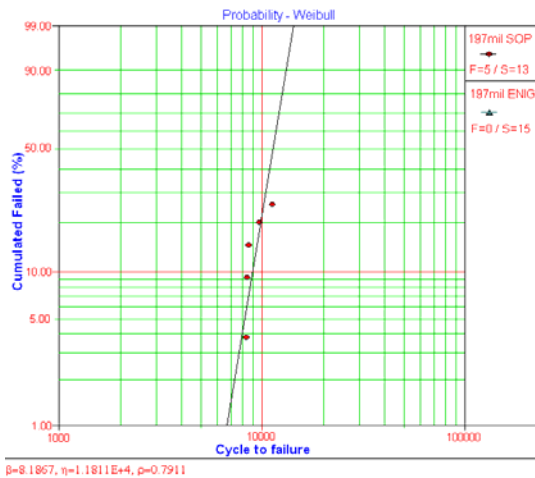


Figure 1. Weibull plot for Lead-free 2209FCBGA package.

In order to confirm the solder joint fatigue failure, additional destructive failure analyses, such as dye penetration and micro cross-section analysis, are carried out. According to the dye penetration analysis result, SOP finished samples have solder joint fatigue failure underneath the die shadow area and fatigue cracks were already propagated after certain cycles of thermal loading as shown in Figure 2 (a). However, the ENIG finished samples have no fatigue failure up to ATC 10,823 cycles and show pad crater at test board side and the interfacial fracture which is not solder joint fatigue failure as shown in Figure 2 (b). Although the ENIG surface finish has a potential risk of brittle failure, the long-term reliability test result clearly shows that the ENIG surface finish has better board level reliability performance than the SOP finish due to controlled diffusion across the barrier metal layer.

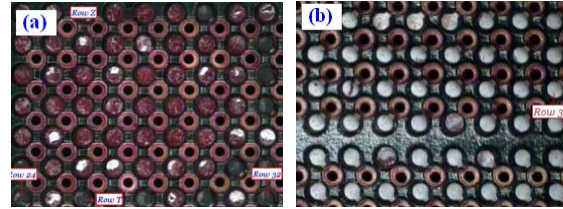


Figure 2. Dye penetration result. (a)SOP finished at ATC 8,617 cycles and (b)ENIG finished at ATC 10,823 cycles of 2209FCBGA package.

3.2 Thermal Aging Test for IMC Growth

The short-term reliability performance of the lead-free solder joints still remains a challenge because of the characteristics of SAC solder material itself. Therefore, the mechanical shock test for SAC305 with SOP finished substrate solder joint is carried out after a certain aging treatment in order to address the problem. In this experiment, the high-end FCBGA package test vehicle is used after the loading time and temperature controlled isothermal aging treatment. Table 3 shows test vehicle information.

Table 3. Mechanical shock test vehicle information.

PKG type	1849pin FCBGA	PKG body	45x45mm ² 1mm pitch
ASIC die	17.3x17.3mm ²	PKG structure	2pc Cu heat spreader
Substrate	2/2/2 build up (1.1mm)	Pad structure	SMD SOP finish
FC solder	SAC305	BGA solder	SAC305
Test board	8.5x8.5inch ² (8 layer) High Tg FR-4	Board pad structure	NSMD OSP finish

The surface mounted 1849FCBGA test vehicles were subjected to the board level mechanical shock testing in accordance with the requirements set forth by JESD22-B110 standard. The shock testing was conducted by using a shock machine which applies positive and negative shocks of prescribed pulse duration and peak acceleration to the boards as shown in Table 4. Each of the five test samples was subjected to two peak accelerations with duration of half sine waveform pulses [11]. Table 4 shows the shock test matrix and its result with and without isothermal aging.

Some relationship between the failure rate and the aging temperature and acceleration peak can be seen as shown in Figure 3 (a) and (b), respectively. However, lower temperature aged test at 100°C shows higher failure rate than the temperature aged test which was conducted at 150°C. In order to

understand the effect of aging temperature on the failure rate, detailed failure analysis, dye penetration and Scanning Micro Electroprobe (SEM) analysis, were carried out.

Table 4. Mechanical shock test matrix and result.

Acceleration peak/pulse	Aging temp (°C)	Aging time (hr)	Fail/Pass
340G/ 1.2ms	No	No	0/5
	150	500	0/5
	100	1000	1/5
	150	1000r	0/5
500G/ 1.0ms	No	No	0/5
	150	500	0/5
	100	1000	3/5
	150	1000	1/5

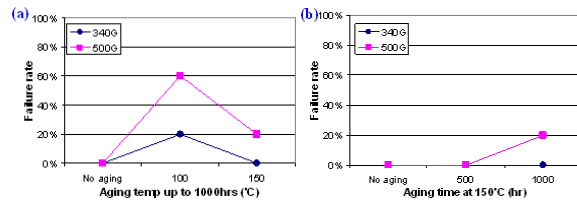


Figure 3. Mechanical shock test result. (a)effect of aging temperature and (b)effect of acceleration peak.

4. Discussion

4.1 Effect of Diffusion Barrier Metal Layer on IMC Growth

The growth of IMC at the SAC305/Cu interface is understood as diffusion at the grain boundary. According to Choi *et al.*, the thickness of IMC at the valley region of the scallop-like IMC layer increases abruptly and is almost constant at the hill region of the scallop-like IMC layer. Eventually, IMCs grow as a layer type after specific thermal loading because the radius of curvature at both hill and valley regions are almost equal [12]. However, the IMC layer growth at the SAC305/Ni interface shows the effect of the Ni barrier metal layer. The Ni layer contributes to the prevention of the IMC layer growth but eventually approximately 20% thickness increment was detected. However, the SOP finished samples with no barrier metal layer showed almost 2 times thicker IMC layer after the ATC 10,000 cycles as shown in Figure 4. It can be concluded that the ENIG surface finished samples have longer solder joint lifetimes compared to the SOP finished and have no solder joint fatigue failures up to the ATC 10,823 cycles because the Ni barrier metal layer prevents rapid IMC layer growth from the long-term reliability point of view.

It has been reported that ENIG surface finish might be potential risks because of an interfacial fracture failure due to porous IMC morphology especially when an external force is applied to the isothermal aged samples which have the Ni barrier metal layer [13]-[17]. Therefore, there is a trade-off for the Ni barrier metal layer application in package substrate between the long-term temperature cycle reliability and the short-term mechanical reliability.

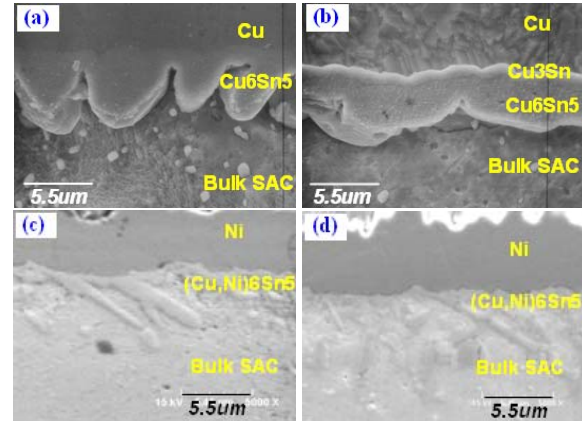


Figure 4. SAC305 solder IMC layer comparison. (a)on Cu at 0 cyc, (b)on Cu at 10,000 cyc, (c)on ENIG at 0 cyc, and (d)on ENIG at 10,000 cyc.

4.2 Effect of Thermal Aging on IMC Growth

According to the dye penetration analysis results, all failures for non-aged and 150°C aged tests are found at the corner of the packages and their failure modes are pad craters at test board side as shown in Figure 5 (a). It can be seen that the dielectric material of the test board is more brittle than the solder joint strength between the SAC305 solder and SOP finished Cu substrate resulting in the pad crater during the mechanical drop test. However, 1000hrs aged test at 100°C shows an interfacial IMC fracture at the interface between the very thin Cu₃Sn and the scallop-like Cu₆Sn₅ as shown in Figure 5 (b). It can also be seen that the very thin Cu₃Sn and the scallop-like Cu₆Sn₅ interface may not resist an external impact and the interfacial fractures are created during the drop test.

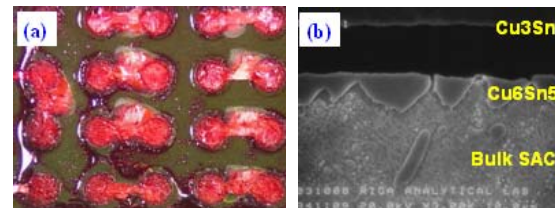


Figure 5. Failure mode of thermal aged shock test. (a)pad crater at 150°C aged test and (b)interfacial IMC fracture at 100°C aged test.

The IMC layer growth of SAC305 solder on the SOP finish is evaluated in terms of thermal aging parameters, such as aging time and temperature. The scallop-like Cu_6Sn_5 IMC layer with a $2.8\mu\text{m}$ average thickness is found in as-reflowed solder joint, but a planer Cu_3Sn IMC layer is not found as shown in Figure 6 (a). Duplex IMCs, scallop-like Cu_6Sn_5 layer is adjacent to the bulk SAC solder and planer Cu_3Sn layer which is in contact with Cu, are observed after aging at two aging temperatures and aged time as shown in Figure 6 (b) through (e).

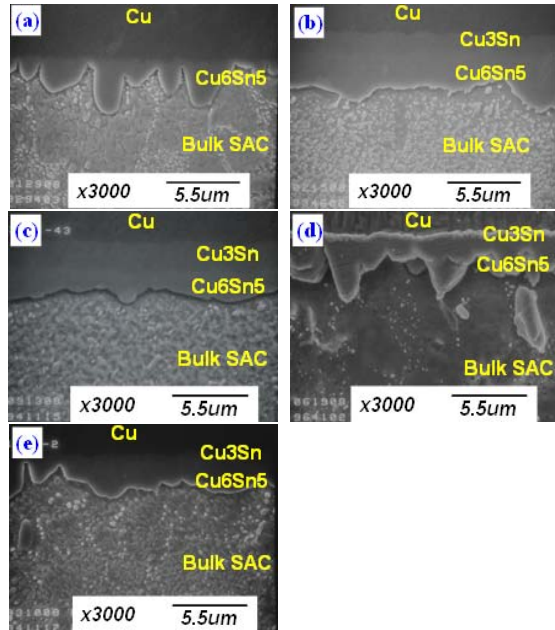


Figure 6. SEM micrographs of SAC305/Cu interface. (a) as-reflowed, (b) aging at 150°C for 500hrs, (c) aging at 150°C for 1000hrs, (d) aging at 100°C for 500hrs, and (e) aging at 100°C for 1000hrs.

For the effect of the aging temperature on the IMC layer growth, the 100°C aged test has very thin Cu_3Sn layer which is less than $1\mu\text{m}$ and scallop-like Cu_6Sn_5 which is around $2.5\mu\text{m}$ after 1000hrs isothermal aging. However, the 150°C aged test has much thicker Cu_3Sn layer compared to the 100°C aged test which is close to $4\mu\text{m}$. But there was no big difference of the Cu_6Sn_5 IMC thickness between both aged tests. The total IMC thickness of the 150°C aged sample has almost twice thicker than that of the 100°C aged sample after 1000hrs aging test as shown in Figure 7. It can be seen that an aging temperature is a dominant factor for the IMC layer growth during the isothermal aging.

For the effect of the aging time on the IMC layer growth, the Cu_3Sn is not observed after reflow and appears at 100°C after aging for 500hrs. A Cu_3Sn formation is inhibited because of the prevention of

Sn diffusion through the Cu_6Sn_5 layer which forms at reflow. In addition, the required activation energy for the Cu_3Sn IMC growth is higher than that of the Cu_6Sn_5 . Therefore, it is confirmed that an aging time is also a valid factor to increase the IMC growth rate. The total IMC thickness has a parabolic relationship with aging time as shown in Figure 8. In addition, a Cu_6Sn_5 is the dominant IMC composition at the beginning of aging, but a Cu_3Sn IMC layer grows faster than Cu_6Sn_5 during the isothermal aging treatment as shown in Figure 8. This observation is consistent with the above grain boundary diffusion controlled model in equation (1) that the IMC layer thickness will follow a $t^{1/3}$ dependence on reflow time.

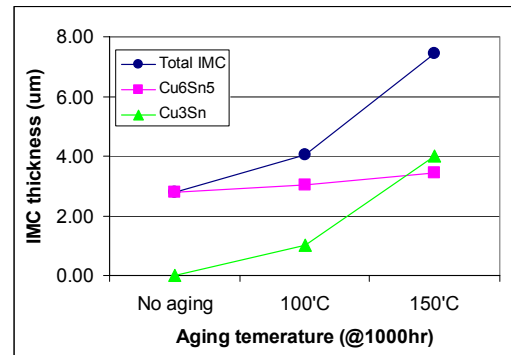


Figure 7. IMC growth of SAC305/Cu interface for 1000hrs aging test.

It also can be seen that a growth rate of overall IMC is almost the same as that of the Cu_3Sn IMC layer. Therefore, the Cu_3Sn is the major IMC component that contributes to the overall thickness of the IMC and the parabolic trend between the IMC thickness and aging time.

5. Conclusion

The determination of the best lead-free solder material and proper substrate surface finish combination selection for the lead-free package applications still needs more investigation. Therefore, the IMC formation of SAC305 lead-free solders and its long-term solder joint reliability and thermal aging effect on the mechanical shock reliability based on different surface finishes are investigated in this study. The ENIG surface finish with the Ni barrier metal layer is shown to be better at preventing rapid IMC layer growth when compared to the SOP finished substrate. The substrate with the Ni barrier metal layer shows a thinner IMC layer and a longer solder joint reliability from long-term reliability point of view.

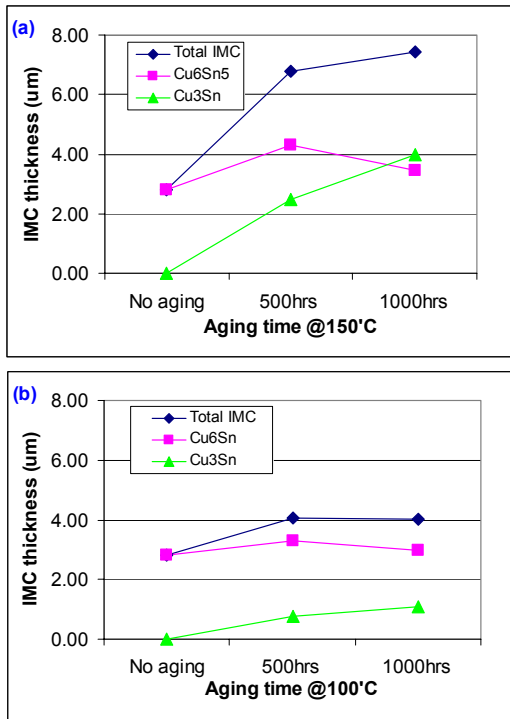


Figure 8. IMC layer growth of SAC305 with SOP finish on Cu substrate, (a)aging test at 150°C and (b)aging test at 100°C.

Aging temperature is a strong factor to decide failure rate and failure mode. Scallop-like η -phase Cu₆Sn₅ IMC is dominated by grain boundary diffusion for transportation through the IMC layer. In addition, the average IMC layer growth was shown to have a strong relationship with aging or reflow time based on the $t^{1/3}$ dependence on time. Also, the 100°C aging test shows a thinner IMC layer than that of the 150°C aging, and interfacial fracture was found at an incomplete IMC interface between the thin Cu₃Sn and scallop-like Cu₆Sn₅ interfaces. In addition, the Cu₃Sn IMC layer which is thinner than 2μm and is considered to be the cause of the interfacial fracture at the Cu₆Sn₅ and Cu₃Sn two-layer IMC.

6. Acknowledgments

The authors would like to thank the support of the NEC Electronics Corporation Package R&D group. We also appreciate the contribution and the support from Dr. Dong Hyun Kim and Dr. Tae Kyu Lee at Cisco for technical discussion.

7. References

1. A.R.Fix, G.A.Lopez, I.Brauer, W.Nughter and E.J.Mittemeijer, "Microstructural Development of Sn-Ag-Cu Solder Joints", *J. Electron. Mater.*, Vol.34, No.2, pp.137-142, February, 2005.
2. D.Li, C.Liu, and P.P.Conway, "Microstructure and Shear Strength Evolution of Sn-Ag-Cu Solder Bumps during Aging at Different Temperatures", *J. Electron. Mater.*, Vol.35, No.3, pp.388-398, March, 2006.
3. D.T.Rooney, D.Geiger, D.Shangguan, and J.Lau, "Metallurgical Analysis and Hot Storage Testing of Lead-Free Solder Interconnections: SAC versus SACC", in *Proc. 58th Electron. Comp. Technol. Conf.*, Orlando, FL, May 27-30, pp.89-98, 2008.
4. M.Schaefer, R.A.Fournelle, and J.Liang, "Theory for Intermetallic Phase Growth Between Cu and Liquid Sn-Pb Solder Based on Grain Boundary Diffusion Control", *J. Electron. Mater.*, Vol.27, No.11, pp.1167-1176, November, 1998.
5. J.H.Lee and Y.S.Kim, "Kinetics of Intermetallic Formation at Sn-37Pb/Cu Interface During Reflow Soldering", *J. Electron. Mater.*, Vol.31, No.6, pp.576-583, June, 2002.
6. D.Shangguan, "Lead-free Solder Interconnect Reliability", *ASM International*, First Edition, pp.31-45, 2005.
7. A.Zribi, A.Clark, L.Zavalij, P.Borgesen, and E.J.Cotts, "The Growth of Intermetallic Compounds at Sn-Ag-Cu solder/Cu and Sn-Ag-Cu solder/Ni interfaces and the Associated Evolution of the Solder Microstructure", *J. Electron. Mater.*, Vol.30, No.9, pp.1157-1164, September, 2001.
8. W.K.Choi and H.M.Lee, "Effect of Ni Layer Thickness and Soldering time on Intermetallic Compound Formation at the Interface between Molten Sn-3.5Ag and Ni/Cu substrate", *J. Electron. Mater.*, Vol.28, No.11, pp.1251-1255, November, 1999.
9. C.E.Ho, R.Y.Tsai, Y.L.Lin, and C.R.Kao, "Effect of Cu Concentration on the Reactions between Sn-Ag-Cu Solders and Ni", *J. Electron. Mater.*, Vol.31, No.6, pp.584-590, June, 2002.
10. Association Connecting Electronics Industries, "Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments", *IPC-9701 standard*, pp.2-8, November, 2001.
11. JEDEC Solid State Technology Association, "Subassembly Mechanical Shock", *JESD22-B110A standard*, pp.2-12, November, 2004.
12. W.K.Choi and H.K.Lee, "Effect of Soldering and Aging Time on Interfacial Microstructure and Growth of Intermetallic Compounds between Sn-3.5Ag Solder Alloy and Cu Substrate", *J. Electron. Mater.*, Vol.29, No.10, pp.1207-1213, October, 2000.
13. A.Choubey, H.Yu, M.Osterman, M.Pecht, F.Yun, L.Younghong, and X.Ming, "Intermetallics Characterization of Lead-Free Solder Joints under Isothermal Aging", *J. Electron. Mater.*, Vol.37, No.8, pp.1130-1138, August, 2008.
14. K.Zeng, R.Stierman, D.Abbott, and M.Murtuza, "The Root Cause of Black Pad Failure of Solder Joints with Electroless Ni/Immersion Gold Plating", *J. Electron. Mater.*, Vol.58, No.6, pp.75-79, June, 2006.
15. Y.D.Jeon, Y.B.Lee, and Y.S.Choi, "thin Electroless Cu/OSP on Electroless Ni as a Novel Surface Finish for Flip Chip Solder Joints", in *Proc. 56th Electron. Comp.*

- Technol. Conf.*, San Diego, CA, May 30-June 2, pp.119-124, 2006.
16. R.J.Coyle, D.E.H.Popps, A.Mawer, D.P.Cullen, G.M.Wenger, and P.P.Solan, "The Effect of Modifications to the Nickel/Gold Surface Finish on Assembly Quality and Attachment Reliability of a Plastic Ball Grid Array, *IEEE Trans. Comp. Packag. Technol.*, Vol.6, No.4, pp.724-732, December, 2003.
 17. P.Snugovsky, P.Arrowsmith, and M.Romansky, "Electroless Ni/Immersion Au Interconnects: Investigation of Black Pad in Wire Bonds and Solder Joints", *J. Electron. Mater.*, Vol.30, No.9, pp.1262-1270, September, 2001.