Effect of Pd Addition in ENIG Surface Finish on Drop Reliability of Sn-Ag-Cu Solder Joint

Sang-Su Ha¹, Jongwoo Park¹ and Seung-Boo Jung²

¹Quality & Reliability Team, Samsung Electronics Co., Ltd., San #24 Nongsea-Dong, Giheung-Gu, Yongin 446-711, Korea
²School of Advanced Materials Science and Engineering, Sungkyunkwan University, 300 Cheoncheon-dong, Jangan-Gu, Suwon 440-746, Korea

The reliability of lead-free electronic assemblies after board-level drop tests was investigated. The effects of different PCB (Printed Circuit Board) surface finishes, viz. ENIG (Electroless Nickel Immersion Gold) and ENEPIG (Electroless Nickel Electroless Palladium Immersion Gold), after reflow and thermal aging (1,000 h at 125 °C) were studied. The increase of IMCs (Intermetallic Compounds) thickness after thermal aging in all of boards. However, as the change of the thickness of the IMC in the ENEPIG board before and after thermal aging was smaller than that of the ENIG board. The results of the drop test, ENEPIG board has greater reliability after reflow than the ENIG board and shows excellent characteristics under all conditions after thermal aging.

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Keywords: board-level drop test, lead-free solder, surface finish, microstructure, thermal aging

1. Introduction

Solder balls in an electronic package not only provide the electrical and mechanical interconnection between the IC package and printed circuit boards, but also play an important role of transmitting signals and emitting light. However, the solder used in the soldering process is brought into contact with the PCB (Printed Circuit Board) or final metal layer of the PCB at a high temperature and IMCs (Intermetallic Compounds) are formed due to their interaction. It has been reported that IMCs with more than the critical thickness have a detrimental effect on the reliability of the joints.¹⁻¹³ In existing electronic appliances, thermal stress has an effect on the durability of the joints, however portable devices such as cell phones, PDAs (Personal Digital Assistants) and PMPs (Portable Multimedia Players) tend to experience problems due to the carelessness of the user or the warping of the board due to the minimization and high-functionality of the electronic devices.²,³ Accordingly, the JEDEC (Joint Electron Device Engineering Council) issued reliability test guidelines for the mechanical shock and drop test,⁴⁻⁷ and research and development on these issues is being actively pursued all over the world. The drop test is performed by applying mechanical shock to a test specimen by fixing it to a shock table and subjecting it to repeated free falls from a regular height. According to the test, when the resistance of the test specimen, measured in real time by means of an electrical connection, exceeds the standard value, it is regarded as a failure. The number of falls that the specimen can withstand before failure is regarded as the lifetime of the specimen.⁸⁻¹³

In the case of an ENIG surface finish, a P-rich Ni layer is formed with a relative increase in the P content in the Ni-P layer according to the reaction between Sn and Ni in the solder after reflow or thermal aging, and it is known that such a P-rich Ni layer is sensitive to external shocks, because of the Kirkendall voids distributed within this layer.¹⁴

Accordingly, in this study, the drop test with or without Pd is performed by jointing a representative lead-free solder consisting of Sn-Ag-Cu on boards with ENIG (Electroless Nickel Immersion Gold) and ENEPIG (Electroless Nickel Electroless Palladium Immersion Gold) surface finishes. Moreover, the mechanical reliability of the solder joints according to the thermal aging and Pd surface finish is evaluated by thermal aging.

2. Experimental

In this study, we used Sn-3.0Ag-0.5Cu (in mass%) BGA balls with a diameter of 450 μm and a rigid PCB (FR-4), which is an SMD (Solder Mask Defined) type board with a thickness of 1t. The pad opening size formed on the board is 380 μm and the pitch size is 1.6 mm. The size of the test board is 132 mm × 77 mm in length and width, respectively, and 64 I/Os per channel are formed. All of the specimens are formed with daisy-chains, which are designed in a structure in which two boards are electrically connected by jointing them together. In order to observe the degree of reliability with or without Pd in the process of applying the surface finish, ENIG is plated at a thicknesses of Ni-P and Au of 5 μm and 0.05 μm, respectively, and ENEPIG is plated with the same thickness of Ni-P and Au and a thickness of Pd of 0.08 μm, as shown in Fig. 1. After alignment and solder ball reflow, the specimen for the test is completed by performing reflow again under the same conditions. The reliability of lead-free electronic assemblies after board-level drop tests was investigated. The effects of different PCB (Printed Circuit Board) surface finishes, viz. ENIG (Electroless Nickel Immersion Gold) and ENEPIG (Electroless Nickel Electroless Palladium Immersion Gold), after reflow and thermal aging (1,000 h at 125 °C) were studied. The increase of IMCs (Intermetallic Compounds) thickness after thermal aging in all of boards. However, as the change of the thickness of the IMC in the ENEPIG board before and after thermal aging was smaller than that of the ENIG board. The results of the drop test, ENEPIG board has greater reliability after reflow than the ENIG board and shows excellent characteristics under all conditions after thermal aging.

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conditions as those described above. One special sample is made for each condition to observe the shape of the IMC, in addition to the specimens used for the drop test and the completed board is treated by thermal aging at 125°C for 500 and 1,000 h.

The drop test board was fixed to the drop table of the drop tester (SD-10, LAB, USA) at the four corners with the mounted packages facing downward, following JESD22-B111.4) The drop table was then released at a certain height and dropped freely to impact on the strike surface repetitively, each time creating a half-sine impact acceleration pulse with a peak acceleration of 900 G (1 G = 9.81 m/s) and an impact duration of 0.7 ms. The drop test condition corresponded to JEDEC drop test condition F. Figure 2 shows the test equipment (a) and acceleration condition (b) for the drop test. When the resistance increases by more than 100 Ω from the initial resistance at the time of shock, it is regarded as a failure. Moreover, when such an increase in resistance is observed at least 3 times out of 5 in the shock test, it is regarded as a failure. After performing the test for 3 specimens in each experiment, the number of drops is measured for each channel. Moreover, in order to observe the stress applied to the board at the time of shock, the strain value is measured after attaching a strain gauge in the center of the board. After the drop test, the samples were potted with epoxy, cross-sectioned, ground, and polished for microstructural observation. In order to examine the IMCs formed at the interface of the solder joint and the fatigue failure mode during the drop test, the cross-sections of all specimens were observed with SEM (Scanning Electron Microscopy). The intermetallic phase was identified with EDS (Energy Dispersive X-ray Spectrometry) and EPMA (Electron Probe Micro Analyzer).

3. Results and Discussion

3.1 Interfacial reactions

Figure 3 shows the cross-section images observed by SEM after reflow and thermal aging for the ENIG and ENEPIG surface finish board. In the case of the pad with the surface finish, Ni-Cu-Sn IMC is formed by the reaction between the Ni of the UBM and the solder. After reflow, (Ni,Cu)Sn (needle type) and (Cu,Ni)Sn (chunky type) IMCs are observed at the interface. In the interfacial reaction between the Ni layer and the Cu-contained solders such as Sn-Ag-Cu and Sn-Cu, ternary IMCs consisting of Cu, Ni and Sn were observed. Jeon et al. reported the formation of (Cu,Ni)Sn and (Ni,Cu)Sn IMCs at the interface between the Sn-4.0Ag-0.5Cu solder and electroless Ni-P layer.15) Ho et al. investigated the effect of a small perturbation in the Cu concentration in the reaction between Sn-3.9Ag-xCu solders (x = 0.2 ~ 3.0 in mass%) and Ni layer during a liquid-solid reaction at 250°C.16) They reported that the slight variation in Cu concentration produced completely different reaction products. Generally, the thickness of the IMC layer at the interface between the solder and substrate is very important in determining the reliability of the whole package because an excessively thick IMC layer is sensitive to stress and sometimes provides initiation sites and paths for the propagation of cracks. Therefore, as the growth of the IMC layer could degrade the reliability of the solder joint, it is essential to study the formation and growth of the IMC layer. In the case of the ENEPIG surface finish board, the IMCs formed at the interface are composed of (Cu,Ni)Sn and (Ni,Cu)Sn, as in the case of the ENIG board, and as the thermal aging time increases, the change of thickness is extremely slight in comparison with that of the other boards. The interface between solder and ENIG/ENEPIG surface finish board was observed by SEM at high magnification for a more precise analysis.

As shown in the SEM images of Fig. 4, a thin layer marked in black is formed between the Ni-P layer and IMCs. This is a P-rich Ni layer, which is formed by the accumulation of the extra P of the Ni-P layer, which is left due to the reactions between Ni and Sn at the interface between the P-rich Ni layer and IMCs. The ratio of Ni to P in the P-rich Ni layer is approximately 3 : 1. It is known that P-rich Ni layers are very weak, causing brittleness and reducing the reliability of the joints.17) According to the SEM magnified images, the thickness of the P-rich Ni layer is approximately 400~500 nm in the case of the ENIG board and there are voids inside. However, it is approximately 100 to 200 nm in the case of the ENEPIG board, which is very thin in comparison with that of the ENIG board.

Figure 5 shows the variation of the thickness of the total IMC (a) and P-rich Ni layer (b) with the thermal aging time.
As the thermal aging time increases in all of the boards, the increase of the IMC thickness. However, as the change of the thickness of the IMC in the ENEPIG board before and after thermal aging was smaller than that of the ENIG board, it is judged that less IMCs are formed, due to the limited diffusion reaction between the Ni-P layer and solder caused by the Pd layer. In other words, little Ni participated in the Cu-Ni-Sn IMC reaction and, thus, a thin P-rich Ni layer is formed. Accordingly, it is judged that the Pd layer controls the diffusion of Ni at the time of the reaction between Ni-P and Sn in the solder and then the P-rich Ni layer and IMCs are formed to a limited extent.

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Fig. 3 Cross-sectional SEM images of the solder joints after as-reflow and thermal aging: ENIG (a), (c), (e) and ENEPIG (b), (d), (f).

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Fig. 4 P-rich Ni layer thickness variation in the solder joint with increasing thermal aging time: ENIG (a), (b), (c) and ENEPIG (d), (e), (f).
Figure 6 shows the top view SEM images of the interfacial IMCs caused by the solder being etched away. It can be seen that the chunky type of \((\text{Cu,Ni})_6\text{Sn}_5\) IMC has a dodecahedral structure in the case of the ENIG board and that its size increases and the ratio of the chunky type of IMC to the needle type of \((\text{Ni,Cu})_3\text{Sn}_4\) IMC increases with increasing thermal aging time.

### 3.2 Drop reliability

Figure 7 shows the graph of the Weibull probability distribution (a, b and c) and box plot (d) for the characteristics of each board after reflow and thermal aging at 125°C for 500 and 1,000 h. The Weibull probability distribution can be represented by a shape parameter \((\beta)\) and a scale parameter \((\eta)\). According to the results of the drop test, the ENEPIG board has greater reliability after reflow than the ENIG board and shows excellent characteristics under all conditions after thermal aging.

According to the results of the drop test in each condition, the ENEPIG board is the least sensitive to temperature and therefore shows better reliability before and after thermal aging. Moreover, it is judged that the Pd layer causes the ENEPIG board to have greater reliability in the drop test than the ENIG board, because of its superior characteristics.
Figure 8 shows the cross-sectional images after reflow and thermal aging for the two boards, in order to observe the failure mode of the drop test. It was observed that all of the specimens of the ENIG board subjected to reflow and thermal aging showed failure between the (Ni,Cu)Sn₄ and P-rich Ni layers.

In the case of an electroless Ni surface finish, the Ni-P layer remains amorphous. However, in the course of reflow, the Ni of the UBM reacts with the Sn of the solder and, accordingly, a phase transformation occurs from Ni-P to Ni₃P (P-rich Ni layer).⁷,¹⁸ As the P-rich Ni layer is weaker than the IMC, it causes cracks, which then spread along the inside of the P-rich Ni layer. In the case of the ENEPIG board, however, most of the cracks are formed inside the solder near the IMC rather than the P-rich Ni layer. The occurrence of an interfacial reaction shows that, in the case of the ENIG board, the P-rich Ni layer that is formed from the interfacial reaction with the electroless Ni is much thinner than that in the ENIG board, and the thickness of the IMC is slightly increased. It is judged that cracks are formed through the inner part of the solder, instead of the P-rich Ni layer, at the time of the drop test, due to the insignificant growth of the IMC and slight formation of a P-rich Ni layer.

Figure 9 showed the EPMA analysis of ENEPIG board after reflow and thermal aging at 125°C for 500 and 1,000h.
atoms in the intermetallic layers. The Cu-Ni-Sn layer contained a small amount of Pd. In the case of the ENEPIG board, the Pd layer acts as a diffusion barrier to the interfacial growth of the IMC and, as cracks are formed through the inner part of the solder instead of the IMC even after thermal aging, it shows high reliability.

Figure 10 shows the paths of the cracks during the drop test and it can be seen that most of the cracks spread from the edge of the solder ball in the most exterior part of the board toward the center and that the shape of the edge ball is changed in comparison with that in the center. As the solder in the most exterior part of the board it is subjected to much more normal stress when the shape of the board is temporarily changed due to shock. Failure occurs in this part first rather than in the solder positioned in the center. The board is warped in the center of the screw portion when the drop table collides with the shock jig in the shock test. As the degree of warping is different at each position of the board, different reliabilities are observed in each portion of the board. Sometimes, cracks occur inside the solder or on the Cu wiring layer, however, in this experiment failure occurred at the interface or through the inner part of the solder in all of the specimens. This experiment shows that the growth of the IMC at the interface of the solder joints has a significant effect on the reliability in the drop impact test.19–21)

4. Conclusion

This study shows the following results after conducting experiments employing different aging times using 450 μm BGA balls with Sn-3.0Ag-0.5Cu solder with or without Pd plating in the surface finish and then performing the drop test. It was found that (Cu,Ni)$_6$Sn$_5$ and (Ni,Cu)$_3$Sn$_4$ IMCs were formed at all of the interfaces of the ENIG and ENEPIG boards and that the thickness increased with increasing thermal aging time. Moreover, it was found that the IMC formed on the ENEPIG board grew more slowly in comparison with that on the ENIG board. According to the results of the drop test, the ENEPIG board showed a smaller change in reliability in comparison with the ENIG board. Moreover, while cracks occurred inside the P-rich Ni layer formed in the joint in the case of the ENIG board, they occurred inside the inner part of the solder in the case of the ENEPIG board. Accordingly, the ENEPIG surface finish board shows better reliability rather than the ENIG surface finish board.

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