The Effects of UBM and SnAgCu Solder on Drop Impact Reliability of Wafer Level Package

Hyun Ho Kim¹, Do Hyung Kim¹, Jong Bin Kim¹, Hee Jin Kim¹, Jae Ung Ahn¹, In Soo Kang², Jun-Kyu Lee², Hyo-Sok Ahn³ and Sungdong Kim³†

¹Nano-Information Technology University & Seoul Technopark, 172 Gongreung, Nowon-gu, Seoul 139-743, Korea
²NEPES Corporation, 654-2 Gak-Ri, Ochang-Eup, Cheongwon-Gun, Chungbuk 363-885, Korea
³Seoul National University of Science and Technology, 172 Gongreung, Nowon-gu, Seoul 139-743, Korea

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Abstract: In this study, we investigated the effects of UBM(Under Bump Metallization) and solder composition on the drop impact reliability of wafer level packaging. Fan-in type WLP chips were prepared with different solder ball composition (Sn3.0Ag0.5Cu, and Sn1.0Ag0.5Cu) and UBM (Cu 10 µm, Cu 5 µm\Ni 3 µm). Drop test was performed up to 200 cycles with 1500G acceleration according to JESD22-B111. Cu\Ni UBM showed better drop performance than Cu UBM, which could be attributed to suppression of IMC formation by Ni diffusion barrier. SAC105 was slightly better than SAC305 in terms of MTTF. Drop failure occurred at board side for Cu UBM and chip side for Cu\Ni UBM, independent of solder composition. Corner and center chip position on the board were found to have the shortest drop lifetime due to stress waves generated from impact.

Keywords: Under Bump Metallization, SnAgCu solder, Wafer Level Package, Drop Impact Reliability

1. Introduction

Recently, the requirements of smaller size, higher performance and lower manufacturing cost for consumer electronics have been increasing more and more. In the packaging industry, several new technologies are proposed to meet these requirements. Wafer level packaging (WLP) is one of the most promising candidates and being widely studied.³ WLP has strong merits in mobile applications since it can provide chip scale package and lower cost of ownership. However, for a mobile application, reliability issues must be fulfilled for example, drop, bending, thermal shock etc. Especially, drop impact reliability should be verified since small mobile products are frequently dropped during daily use.

Drop impact usually induces failures at solder joints since different flex of PCB and chip during drop impact applies stress to solder joints. Therefore, stress concentration at solder joint and micro-structural response of the solder joint have been a major interest in drop reliability research.², ³ In terms of microstructure of solder joint, intermetallic compound (IMC) formation plays an important role in determining the strength of solder joints since IMC has a high strength but brittleness. IMC is a reaction product between under bump metallization (UBM) and solder, which means IMC formation can be controlled by UBM and solder.

In this study, we investigated the effects of UBM and solder composition on the drop impact reliability of WLP. Four kinds of samples with different UBM and solder combination were prepared. Board level drop test was performed and the results were interpreted with statistical analysis and numerical simulation.

2. Experiments

Drop test samples were fabricated through a fan-in type WLP process. The chip size was 5.6×5.6 mm² and solder balls were 14×14 arrayed with 250 µm diameter and 400 µm pitch (shown in Fig. 1). Two kinds of solder ball composition (Sn3.0Ag0.5Cu, Sn1.0Ag0.5Cu) and UBM type (Cu 10 µm, Cu 5 µm\Ni 3 µm) were selected as effective variables for drop impact reliability.

Drop test boards were prepared according to JEDEC standard (JESD22-B111)⁴ and its size was 132×77×1 mm³. Each board has 15 chips mounted on the Cu-OSP finished pads and a daisy chain was designed for \textit{in-situ} measurement of resistance. Each chip was labeled and monitored according to their position on the PCB as illustrated in Fig. 2. Table 1 summarizes the specification of chip and PCB for
this study. Four kinds of chips with different SAC solder and UBM combination (Cu UBM + SAC305, Cu UBM + SAC 105, CuNi UBM + SAC305, CuNi UBM + SAC105) were prepared and two PCBs were drop-tested for each kind of chip. Drop test was performed up to 200 cycles for each test board and the acceleration was fixed at 1500G. The resultant drop lifetime was analyzed with Weibull distribution and the failure mode was investigated with optical microscope and SEM.

Numerical simulation of drop impact on each chip was also performed to evaluate different lifetime behavior which was depending on their location on the test board. Based on the symmetry of PCB layout, one fourth of the test board was selected for the simulation. The simulated strain was calibrated with the strain-gauge measured one at U08 and U09 positions in Fig. 2.

3. Results and Discussion

3.1. Number of drops to failure

In table 2, the number of drops to failure was tabulated according to chip position on the drop test board. Four combinations of UBM and solder ball were expressed in the first column and PCB number 1, 2 in the second column mean two boards were dropped for each combination of UBM and solder ball. All test boards were dropped 200 times and failure cycles at each chip position were recorded. Symbol ‘-’ indicates that chip survived 200 drop cycles.

Table 2 shows that chips with CuNi UBM had less failed chips than chips with Cu UBM. For example, CuNi/SAC305 board had 5 and 6 chip failures out of 15 chips while Cu/SAC305 board had 10 and 13 chip failures. However, the effects of SAC composition on the drop lifetime were not clear when only number of chip failures was taken into account and the further statistical analysis was required.

In terms of chip position, four positions of U06, U07, U09 and U10 showed better drop impact resistance, which was in agreement with general expectation. However, positions next to board fixture (U01, U05, U11 and U15) showed poor drop impact resistance, which will be discussed later with numerical simulation result.

3.2. Weibull plot analysis

Weibull plot is one of the most widely used lifetime distributions. Two parameter Weibull PDF (Probability Density Function) is given by \( f(t) = \beta/\theta \left( t/\theta \right)^{\beta-1} \exp\left(-\left(t/\theta\right)^{\beta}\right) \) where \( \beta \) is a shape parameter and \( \theta \) is a scale parameter. Shape parameter is also equal to the slope of regressed line in a probability plot. When the value of \( \beta \) is less than 1, a failure rate decreases with time, exhibiting early-type failures. With \( \beta > 1 \), a failure rate increases with time, that is, wear-out type failures. Scale parameter has an effect on the abscissa scale of the distribution. When the scale parameter increases with constant shape parameter, the distribution stretches out to the right.

As a measurement of the reliability, MTTF (Mean Time to Failure) is generally used. MTTF is often calculated by dividing the total operating time of the test units by the total number of failures encountered. Although this metric is valid only when the data are exponentially distributed (the failure rate is constant, that is, shape parameter is equal to 1 in a Weibull distribution), it can be used as the sole measurement
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Weibull plots for each combination of solder and UBM are depicted in Fig. 3 and related parameters are listed in Table 3. Shape parameters for all samples are greater than or equal to 1, implicating a wear-out type failure mode. Scale parameters for CuNi UBM are larger than those for Cu UBM. With the assumption of constant shape parameter for all samples, this large scale parameter implies that CuNi UBM has better drop impact resistance than Cu UBM. This interpretation is supported by the Weibull plots in Fig. 3. CuNi UBM plots are shifted toward higher number of drops to failure compared to Cu UBM plots for same SAC composition.

In order to observe the effects of UBM on the drop reliability clearly, drop test data in Table 2 were re-arranged according to UBM type and the cumulative percent failure as a function of drop cycle is illustrated in Fig. 4. As seen in Fig. 4, CuNi UBM shows better drop performance than Cu UBM. MTTF was calculated to be 129 for Cu UBM and 289 for CuNi UBM (Table 4). The enhanced drop performance with CuNi UBM can be attributed to the role of Ni layer in IMC formation. In general, Cu UBM reacts with SAC solder to form intermetallic compounds (IMC) such as Cu₆Sn₅ and Cu₃Sn. Cu₆Sn₅ IMC is usually formed first, followed by Cu₃Sn IMC formation. Both of the internal stress difference between Cu₆Sn₅ and Cu₃Sn IMCs and void formation during Cu₃Sn IMC growth are known to
be one of the sources of fracture during drop impact.\textsuperscript{5,6} Ni layer between Cu UBM and SAC solder acts as a diffusion barrier and retards the Cu\textsubscript{3}Sn IMC formation, which results in improved drop performance. This suppression of Cu\textsubscript{3}Sn IMC formation with Ni was also observed in Ni addition to solder composition.\textsuperscript{6}

While UBM type affected drop performance noticeably, solder composition showed little effects on the drop performance. In Fig. 3, probability plots were close to each other and crossed each other at around 100 numbers of drops to failure. As for Cu UBM, SAC105 showed earlier failure and lower shape parameter (slope of the regression line). However, as for Cu\textsubscript{3}Ni UBM, SAC305 showed earlier failure and lower shape parameter (table 3) than SAC105. In order to clarify the effects of solder composition, drop test data in table 2 were also re-arranged according to solder composition and illustrated in Fig. 5. Although SAC105 began to fail at earlier drop cycle than SAC305, MTTF and scale parameter showed better drop performance for SAC105 (table 5). This longer MTTF for SAC105 is in accord with the other studies.\textsuperscript{5,6} Since SAC solder becomes more ductile with low Ag contents, SAC105 is able to absorb drop impact shock more effectively, which results in the better drop performance.

### Table 5. MTTF and Weibull parameter for Fig. 5.

<table>
<thead>
<tr>
<th></th>
<th>SAC305</th>
<th>SAC105</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTTF</td>
<td>172.827</td>
<td>203.438</td>
</tr>
<tr>
<td>Shape parameter</td>
<td>1.336</td>
<td>1.068</td>
</tr>
<tr>
<td>Scale parameter</td>
<td>188.121</td>
<td>208.689</td>
</tr>
</tbody>
</table>

### 3.3. Failure analysis

Failure sites after drop test were observed by optical microscope and SEM. In case of Cu UBM, most of the failure occurred at PCB side. As shown in Fig. 6, cracks propagated mostly along the interface between Cu pad and solder, and partly into bulk solder. In contrast to PCB side failure with Cu UBM, major failure site with Cu\textsubscript{3}Ni UBM was chip side (Fig. 7). As for Cu\textsubscript{3}Ni\textsubscript{3}SAC105, cracks were observed at both side of PCB and chip but the final failure occurred at chip side (Fig. 7. (a)). Samples with Cu\textsubscript{3}Ni\textsubscript{3}SAC305 showed only chip side failures (Fig. 7. (b)). This failure site transition from PCB to chip with the addition of Ni layer is an interesting phenomenon and may be related to the IMC formation. The composition and thickness of IMC layer are believed to be a key factor for this transition and now under additional investigation.

### 3.4. Numerical simulation

During the board level drop test, three major mechanisms are known to cause drop failure. Firstly, the bending or elongation stress induced by the flex difference between chip and board. Secondly, the inertia force due to gravitational acceleration. Thirdly, stress waves generated form impact.\textsuperscript{7} The drop lifetime at a certain chip location on the board is dependent on the specific major mechanism.
since each mechanism gives different influence to different chip location. From table 2, it was found that the drop failure occurred first at corner position such as U01, U05, U11, U15 and then followed by center position of U08. Both end of the middle row, that is, U06 and U10 were the last failure position. No drop failure was observed in U10 and only one failure in U06.

The dependence of drop performance on the chip location is analyzed by the numerical simulation. Since the board has a symmetric layout, only 1/4 of the board was simulated. The material properties used for the simulation are summarized in Table 6. Von Mises stress as well as strain energy distribution were calculated through modal analysis and an example of ANSYS simulation for drop test is illustrated in Fig. 8. As observed in experiments, the corner position suffered the highest stress. In a modal analysis, 1st and 2nd resonance states induced by strain waves were considered. The simulation showed the same failure order as the experiment, which implies stress waves were the key mechanism in drop impact reliability. The details of the simulation work will be published elsewhere.

Table 6. Material properties used for the drop simulation

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Modulus (N/mm²)</th>
<th>Poisson ratio</th>
<th>Density (kg/mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn3.0Ag0.5Cu</td>
<td>48,000,000</td>
<td>0.3</td>
<td>0.0000074</td>
</tr>
<tr>
<td>Sn1.0Ag0.5Cu-0.05Ni</td>
<td>33,400,000</td>
<td>0.3</td>
<td>0.00000736</td>
</tr>
</tbody>
</table>

Fig. 8. Von Mises stress distribution in 1/4 of a test board with SAC105. Black hole at upper right corner is the drop board fixture and left lower corner is the center of the board.

4. Conclusions

The effects of UBM and solder composition on the drop impact reliability were investigated. Two kinds of UBM (Cu UBM and Cu\Ni UBM) were considered and Cu\Ni UBM was observed to have superior drop performance to Cu UBM. This improvement of drop performance by Ni insertion could be attributed to suppression of Cu₃Sn IMC due to Ni diffusion barrier. In case of solder composition experiment, there was no noticeable difference between SAC105 and SAC305 solder composition. However, SAC105 was better than SAC305 from a statistical viewpoint. The corner position next to board fixture was found to be the most vulnerable to drop failure, which was understood by modal analysis with stress waves.

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References