Study of Five Substrate Pad Finishes for the Co-design of Solder Joint Reliability under Board-level Drop and Temperature Cycling Test Conditions

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Abstract
The current paper evaluates the impact on solder joint reliability (SJR), using board-level drop test, temperature cycling on board (TCoB) test, and component-level high-speed solder ball shear (HSSBS) test, of five existing and under-development substrate pad finishes including Electrolytic Nickel-Gold (NiAu), Organic Solderability Preservative (OSP), stencil printed Solder-on-Pad (SoP), Immersion Tin (ImSn) and Electroless Nickel-Electroless Palladium-Immersion Gold (NiPdAu). The board-level drop test was performed following standard JEDEC conditions with 1500G/0.5ms. The TCoB test was performed following IPC-9701 with -40°C-125°C and 15 minutes dwell/ramp. The HSSBS test was performed using Dage 4000-HS machine with 500mm/s shearing speed and 30µm shearing height.

It is seen from drop test results that NiAu leg gives the poorest SJR. All of the other four pad finishes give very satisfactory drop test durability. In TCoB test results, however, it is observed that NiAu gives the best SJR. OSP gives very poor SJR as compared with the other four counterparts whose 2-parameter Weibull characteristic lives exceed 2000 temperature cycles with significant margin. Subsequent process improvements were made in an effort to improve the SJR of OSP in TCoB test. However, even with these improvements the characteristic lives of two improved OSP testing legs only marginally pass the SJR requirement of TCoB. HSSBS test was also performed to understand the resistance to brittle intermetallic compound (IMC) failure of the five finishes under time zero and ageing condition. It is observed that although SoP sees very good SJR in both drop and TCoB tests, it shows bad resistance to brittle IMC failure in HSSBS test. Encouragingly, NiPdAu, which shows good SJR in both drop and TCoB tests, is also found to give excellent resistance to brittle IMC failure in HSSBS test even after ageing at 125°C for 1000 hours.

Key words: pad finish, NiAu, OSP, SoP, Immersion Tin, NiPdAu, solder joint reliability, IMC, drop test, temperature cycling test, high-speed solder ball shear test

1. Introduction
Electronic package development is going extreme in miniaturization. However, the stringent and even increasing reliability requirements are never relaxed. Meeting one reliability requirement may compromise another. So the overall reliability of a package is always a trade-off result after considering every aspect of the reliability requirements. The board-level drop test and TCoB test are currently two most prevailing board-level reliability tests. Board-level SJR of a package is influenced by many factors including both design and material. However, the trend of package miniaturization does not leave much space for design to play around with to improve board-level reliability. Change of material selection is a viable way, but may require large DOE matrix to make sure certain material set can meet all the reliability requirements, at least, with minimum allowable margin.

Pad finish is the direct interface between package and solder or between solder and PCB. It plays a significant role in determining the type and characteristics of IMC formed at those interfaces and even the microstructure of bulk solder joint. In both TCoB and drop tests it is understood that crack near or at the substrate/solder interface is the most common failure mode. Therefore, board-level SJR can be greatly enhanced by selecting the appropriate pad finish material. It should be noted that change of substrate solder pad finish material, however, will not impact other gauges of package performance such as warpage. It is therefore an excellent choice when board-level SJR needs to be improved without impacting the overall package design and other reliability aspects.

The focus of study in this paper is given to the impact of substrate pad finish on board-level SJR of CSP packages. Several substrate pad finishes exist in production or R&D. NiAu, be it processed by electrolytic or electroless/immersion, has been used for long on BGA packages for good wirebondability, solderability and ability to sustain the high temperature during assembly. With the trend that more and more packages are going into mobile applications, recent attention was paid to OSP pad finish, known for its enhancement of board-level drop reliability [1-2]. Although not widely in mass production use, some other pad finishes are under development. Those pad finishes include SoP, Sn and NiPdAu. Similar as wafer level bumping, SoP can be formed by stencil printing or plating at the substrate level. Sn, as a pad finish material, can be formed by electroplating or immersion process. Initial study in [2] found that its drop test performance is even better than OSP, but the TCoB test performance is unknown in that study. NiPdAu is usually processed by electroless Ni, electroless Pd and Immersion Au [3-5]. So more popularly it is called ENEPiG. In this finish Ni layer bonds securely to the copper metallization, while the Pd layer serves as a diffusion barrier for reducing or preventing Ni from out diffusing during thermal processes. The final Au layer adheres to Pd layer and readily receives solder or bonding wires. Recently some research has been done for NiPdAu.
pad finish for laminate packages. It was demonstrated in [3, 6] that NiPdAu is potentially an excellent pad finish material because it has both good solderability with lead-free solders and wirebondability using all of the three popular wire metals, Au, Cu and Al. In the study in [3, 5, 6] it was found that Au wireboneding on NiPdAu has good reliability even after thermal ageing and cycling. Cu wireboneding was also found to perform similarly well on NiPdAu [6]. The thickness of deposited Pd was found to have significant impact and less than 0.2µm was recommended in [3] and only 0.06µm was used in [5]. Otherwise, brittle interface could be easily formed and lead to brittle cracking. NiPdAu as BGA pad finish was also studied and evaluated mainly using ball shear/pull test in [3, 5, 7]. In those literatures, however, no studies of the pad finish impact on SJR in both drop and TCoB tests were conducted. This paper aims to fill up the vacancy and share our evaluation results on the board-level reliability of the five finish materials mentioned earlier. Board-level drop test and TCoB tests are the major board-level tests required by most package qualifications. These two tests are adopted in this study to gauge the performance of the five pad finishes. HSSSBS test, which simulates impact loading on solder ball, is also performed to understand the resistance to brittle IMC cracking for the five finishes.

2. Drop Test

The study of substrate pad finish impact in this paper employed an 11x10.5mm wCSP test vehicle whose ball layout is shown in Figure 1. The test vehicles were assembled with low-Ag lead-free solder composed of 98.48%-Sn/1%-Ag/0.5%-Cu/0.02%-Ni, which is known to be soft and can improve board-level drop reliability. Drop tests were performed following JESD22-B111 board-level drop test standard. The JEDEC drop test setup and testing conditions are shown in Figure 2 and 3 respectively. The drop test matrix is listed in Table 1 with all the five pad finishes mentioned in previous section. Table 2 shows us the cross-section pictures of the five pad finishes. Those cross-section pictures were taken at the solder pad region of as-received substrates. It should be noted that the SoP pad finish in this study was formed by stencil printing of SAC305 solder paste followed by reflow process. Therefore a dome consisting of solder SAC305 is seen in the cross-section picture.

Examination of repeatability of drop testing conditions was firstly performed to ensure consistency. Good repeatability was achieved with high Cpk value as shown in Figure 3. Then 300 drops were performed for each of the five legs with four pieces of PCB assembly in each leg. Failure analysis found that the solder joint crack, occurred at the IMC layer (Figure 4), is the primary failure mode. A comprehensive data analysis was performed using a variety of methods including number of drops up to first failure, Weibull analysis of all the components on each PCB, Weibull analysis of group E&F on each PCB, arithmetic mean of Group E&F as well the number of survived units. The results comparison based on those data analysis methods is shown in Figure 5 and 6. It is noticed that NiAu leg encountered very early failures. During the test electrical discontinuity was detected even after two drops in three PCB assemblies. Although these very early failures could be attributed to experimental errors that induced during ball mount process, SMT assembly process, or by possible test board quality issue, those five legs were subject to the same assembly process and mounted onto the same batch of PCB test board. The other four legs showed overall good drop test reliability, although one of the components in OSP leg failed as early as 11 drops. The best drop test performance is seen on ImSn leg. Failure for this leg did not occur until 48 drops. It is observed that OSP, ImSn and SoP show similar drop test reliability. The similar drop test performance could be due to the fact all the three pad finishes produced the same type of Cu-Sn IMC at the solder/pad interface. This is proved by subsequent SEM analysis on IMC microstructure as shown in Figure 8b to 8d. Overall drop performance of NiPdAu, although seems not as good as that of OSP, ImSn and SoP, is highly satisfactory. There was no failure occurrence to NiPdAu leg before 31 drops, which is much better than NiAu and even better than OSP in terms of first failure occurrence. The good drop test reliability, together with the excellent wirebondability and solderability, makes NiPdAu potentially an excellent solution for BGA packages targeted at mobile applications.
Table 1: Drop test matrix

<table>
<thead>
<tr>
<th>Leg #</th>
<th>Leg Name</th>
<th>Substrate Pad Finish</th>
<th>Process Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NiAu</td>
<td>NiAu</td>
<td>Electrolytic</td>
</tr>
<tr>
<td>2</td>
<td>OSP</td>
<td>OSP</td>
<td>N.A.</td>
</tr>
<tr>
<td>3</td>
<td>SoP</td>
<td>SoP</td>
<td>Printing (SAC305)</td>
</tr>
<tr>
<td>4</td>
<td>ImSn</td>
<td>Sn</td>
<td>Immersion</td>
</tr>
<tr>
<td>5</td>
<td>NiPdAu</td>
<td>NiPdAu</td>
<td>ENEPIG</td>
</tr>
</tbody>
</table>

Table 2: Cross-section picture of the 5 solder ball pad finishes

<table>
<thead>
<tr>
<th>Leg #</th>
<th>Leg Name</th>
<th>Cross-section view of pad finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NiAu</td>
<td><img src="image1" alt="Cross-section view of NiAu pad" /></td>
</tr>
<tr>
<td>2</td>
<td>OSP</td>
<td><img src="image2" alt="Cross-section view of OSP pad" /></td>
</tr>
<tr>
<td>3</td>
<td>SoP</td>
<td><img src="image3" alt="Cross-section view of SoP pad" /></td>
</tr>
<tr>
<td>4</td>
<td>ImSn</td>
<td><img src="image4" alt="Cross-section view of ImSn pad" /></td>
</tr>
<tr>
<td>5</td>
<td>NiPdAu</td>
<td><img src="image5" alt="Cross-section view of NiPdAu pad" /></td>
</tr>
</tbody>
</table>

3. Temperature Cycling on Board Test

The TCoB test for pad finish impact study employed similar testing matrix of the drop test with some added legs as shown in Table 4. In Table 4, a larger CSP package with 5 more rows of solder balls was added to the original drop test matrix. Furthermore, two "RE" legs were also added later to improve the SJR of OSP in TCoB test. The "RE" legs were improved in some process parameters based on the recommendations of packaging engineers.

The TCoB test was conducted under -40°C-125°C and 15 minutes dwell/ramp. The PCB test board used was 1.1mm following PCB board thickness usually used by DIMM module.

The TCoB test was conducted until enough data was generated for statistical analysis. Failure analysis on failed samples shows that the failure mode is very typical solder joint crack near the substrate side as shown in Figure 7. But unlike the drop test, the crack in TCoB test initiates and propagates inside the bulk solder material. Microstructure
analysis of IMC was also performed for both time zero and after-TCoB-test assemblies. Figure 8 (a-e) shows the comparison of IMC microstructure for each leg before and after TCoB test. In NiAu leg, the initial needle-like Cu-Ni-Sn IMC in Figure 8 (a) has small grain size and dense distribution. Literature survey in [8] shows that this needle-like Cu-Ni-Sn IMC is (Ni,Cu)_2Sn. During TCoB test, some chunky shape (Ni,Cu)_2Sn IMC is formed at the expense of the needle-like (Ni,Cu)_2Sn [8]. However such chunky shape IMC only appears in selective locations and the major needle-like IMC still has fine grain size and dense distribution. OSP, ImSn and SoP all enable direct solder attachment to copper pad. Therefore, the IMC formed at these finishes are the same as shown in Figure 8 (b-d). Comparing Figure 8 (b-d) and findings in literature [9], it is understood that the scallop-like IMC at time zero in Figure 8 (b-d) is Cu_6Sn_5. Because there is no Ni layer to prevent the inter-diffusion between copper and solder, the IMC growth rate is reported to be much higher in these three pad finishes than that in NiAu [10]. It is therefore observed from Figure 8 (b-d) that in OSP, ImSn and SoP legs IMC size was greatly increased due to thermal effect and stress induced in temperature cycling test [11]. For NiPdAu, it was reported in [5, 12] that similar as the NiAu the IMC formed with Sn-Au-Cu solder is also Cu-Ni-Sn. However, the current IMC morphology as shown in Figure 8 (e) is quite different from that given in [5, 12]. In [5], the IMC formed between NiPdAu and SnAg3.5Cu0.5 solder is small in grain size and much smaller than the grain size of IMC formed on OSP. It is also shown in the study of [12] that the Cu-Ni-Sn IMC formed between NiPdAu and SAC305 is needle-like. However, the current study found that the IMC morphology as shown in Figure 8 (e) is almost is pyramid-like. Furthermore, after TCoB test, the IMC grain size seems unchanged. Further study will be performed to analyze the IMC.

The 2-parameter Weibull plots for all the eight legs are given in Figure 9 and the Weibull parameters compiled in Table 5 based on 90% confidence level. From Figure 9 it is seen that NiAu, OSP, SoP, ImSn and NiPdAu have characteristic lives of 2912X, 1124X, 2283X, 2287X and 2266X respectively. The results clearly show that although NiAu gives the worst drop test reliability, it shows superior performance in the TCoB test. Therefore, in applications where temperature cycling is the major concern over SJR, NiAu should still be the primary choice for pad finish material. SoP, ImSn and NiPdAu also produced excellent SJR in TCoB test with all the three giving similar performance. The similarity of SJR of SoP and ImSn is probably due to the their direct solder attachment to copper with no influence of other material, unlike the situation in OSP leg where OSP material might disperse into the solder and impact the reliability. Together with the drop test results shown earlier, it is evidenced that SoP, ImSn and NiPdAu can meet both strict drop reliability and TCoB test reliability requirements. Especially for NiPdAu, in view of the good wirebondability and solderability [3-7], and good board-level SJR in both drop and TCoB test, it may become the ideal choice when all of these reliability requirements are to be met. In the TCoB testing of OSP pad finish, it performed worst although it had overall good drop test reliability. Leg 2 and 6, which were the initially tested legs for OSP finish, saw many failures before 1000 cycles or even 500 cycles. It is known that OSP is an organic material and will be removed from copper during reflow soldering. Therefore it was postulated that OSP, ImSn and SoP legs should give similar SJR in TCoB test since each enables direct solder attachment to copper. This similarity was observed in the drop test where solder joint crack in the IMC is the mode of failure. Such similarity of SJR was also observed in SoP and ImSn in TCoB test as mentioned earlier. However, the current experimental results of TCoB test clearly show significantly inferior SJR of OSP to ImSn and SoP. It is observed that solder joint crack in TCoB test usually occurs in the solder neck area that is some distance away from the IMC and is actually inside the bulk solder as shown in Figure 7. It is also understood that OSP thickness control is a challenge in the supplier side and the thickness is very difficult to measure for quality control purpose in the user side. Therefore we hypothesized that the OSP layer in Leg 2 and 6 substrates could be too thick to be completely removed in reflow soldering such that the remaining OSP or its resultant residues dispersed into the microstructure of the solder and somehow made it more prone to fatigue failure. Two process changes aimed at removing OSP completely were proposed. The first change was to increase the peak temperature of ball mounting reflow process by 5 to 10 degree C, while the second change was to increase the dwell time above 217C by 5 seconds in package SMT onto PCB. The first and second changes are name 6-RE1 and 6-RE3 in Table 4. Assemblies of Leg 6-RE1 and RE3 were subject to TCoB test again. This time no failure was logged before 1000 cycles. From the Weibull plot and parameters in Figure 9 and Table 5, it is seen that both improvements give characteristic lives much more than the original OSP legs. With the later first failure and improved characteristic life, the solder joint reliability of OSP finish can now meet the requirements of most customers. However, it should be noticed that even with these improvements, SJR of OSP is still not as good as that of SoP and ImSn. IMC analysis was also performed on RE1 and RE3. It is shown in Figure 8 (f) that no difference in IMC morphology is found between the original OSP (Figure 8 (b)) and OSP based on RE1 and RE3 in Table 4. Assemblies of Leg 6-RE1 and RE3 were subject to TCoB test again. This time no failure was logged before 1000 cycles. From the Weibull plot and parameters in Figure 9 and Table 5, it is seen that both improvements give characteristic lives much more than the original OSP legs. With the later first failure and improved characteristic life, the solder joint reliability of OSP finish can now meet the requirements of most customers. However, it should be noticed that even with these improvements, SJR of OSP is still not as good as that of SoP and ImSn. IMC analysis was also performed on RE1 and RE3. It is shown in Figure 8 (f) that no difference in IMC morphology is found between the original OSP (Figure 8 (b)) and OSP based on RE1 and RE3 changes. This probably indicates that IMC might not be the cause of TCoB reliability improvement. It is probably the microstructure of the bulk solder that improved the SJR in TCoB test. Future study needs to be carried out to understand this.

Table 4: Additional legs of TCoB test for pad finish study

<table>
<thead>
<tr>
<th>Leg #</th>
<th>Pad Finish</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>OSP</td>
<td>Large package size 11x12.5mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>More solder ball: 90B (15x6)</td>
</tr>
<tr>
<td>6-RE1</td>
<td>OSP</td>
<td>On top of Leg 6, increase the peak temperature by 5 - 10C in ball mount reflow</td>
</tr>
<tr>
<td>6-RE3</td>
<td>OSP</td>
<td>On top of Leg 6-RE1, increase dwell time above 217C by 5 -10 sec during SMT reflow</td>
</tr>
</tbody>
</table>
Figure 7: Solder joint crack in TCoB (Leg 4: ImSn)

a: Leg 1-NiAu (Left: Time Zero, Right: After TCoB)

b: Leg 2/6-OSP (Left: Time Zero, Right: After TCoB)

c: Leg 3-SoP (Left: Time Zero, Right: After TCoB)

d: Leg 4-ImSn (Left: Time Zero, Right: After TCoB)

e: Leg 5-NiPdAu (Left: Time Zero, Right: After TCoB)

f: Leg 6 OSP RE1 (left) and RE3 (right) time zero (top) and after TCoB (bottom)

Figure 8: SEM scan (6K Magnification) of IMC

Leg 1: NiAu, 11x10.5mm wCSP with 60 balls

Leg 2: OSP, 11x10.5mm wCSP with 90 balls
4. High-speed Solder Ball Shear Test

HSSBS test was performed using Dage 4000-HS machine with 500mm/s shearing speed and 30µm shearing height as shown in Figure 10. The reason of using high-speed shearing is to simulate the strain rate when solder is subject to sudden loading such as the case in drop test. Because of the high strain rate and strain-rate hardening effect of solder, load is effectively transferred to the solder/pad interface and IMC failure, the primary failure mode in drop test, can be observed [10, 13-14]. Therefore HSSBS provides a quick evaluation tool with which IMC strength under high strain-rate can be quickly evaluated. It is also found in [10, 13-14] that the occurrence of IMC failure mode in HSSBS test has some degree of correlation with the drop test results.

The same testing matrix as used in drop test was used for the HSSBS test. For each leg 24 solder balls from 4 different
packages were sheared. Two groups of testing were performed with the first group coming from time zero or as-received packages and the second group aged at 125°C for 1000 hours. Three failure modes, namely bulk solder failure, IMC failure and partial-IMC-partial-bulk-solder failure, were observed. Typical failure pictures of bulk solder and IMC are shown in Figure 11. The testing results are shown in Figure 12.

From Figure 12 it is observed by looking at the time zero data that NiAu finish is relatively good in terms of IMC failure occurrence although it gave poorest SJR in drop test. Interestingly SoP pad finish, which showed very good drop test reliability, was found to give the most IMC failures at time zero in HSSBS test. While several IMC failures were found in OSP leg at time zero test, no such failure mode was observed in ImSn and NiPdAu legs that showed good resistance to brittle failure under high-speed shear test at time zero.

Aging the samples for 1000 hours at 125°C is expected to increase the IMC thickness similarly as temperature cycling [11] and thus generates more brittle failures in HSSBS test. It is observed from Figure 11 that all the pad finishes did generate more IMC failures except NiPdAu. Same as the results from time zero samples, aged NiPdAu still did not give any brittle IMC failure, which shows very good resistance to impact loading even after thermal ageing. The robustness of NiPdAu found in HSSBS study may have some correlation with the IMC analysis in TCoB test where we did not observe a significant growth in IMC for NiPdAu pad finish. SoP finish in HSSBS study after ageing is still the worst, giving half of the failure mode as IMC failure. NiAu, OSP and ImSn also saw increase in IMC failure modes after ageing with NiAu seeing only slight increase.

The trend observed in the current HSSBS test for both time zero and aged samples is consistent with the findings in [5, 7, 12]. However, the observation is that the ranking of the five pad finishes in HSSBS test does not show a good correlation with that in board-level drop test. This probably indicates that using HSSBS test to gage the drop test performance of different pad finishes might not provide a good insight into their real SJR in drop test.

5. Summary and Conclusions

Board-level drop test, TCob test and HSSBS test were performed to evaluate the impact of substrate pad finishes on SJR. It is found in the current study that:

1. NiAu gave worst SJR in board-level drop test. OSP, SoP, ImSn and NiPdAu showed overall good performance in drop test.

2. NiAu enabled the best SJR in TCoB test. SoP, ImSn and NiPdAu performed similarly with good SJR.

3. SJR of OSP in TCoB test showed strong dependency on reflow soldering conditions. However, even with improved process parameters, OSP still resulted in much less reliability than the other four.

4. NiAu should still be the primary choice when temperature cycling load is the major concern in board level and no impact loading like drop is likely to happen in the field application.

5. SoP, ImSn and NiPdAu can meet SJR requirements from both board-level drop test and TCoB test.

6. Failure analysis on time zero and TCoB tested samples showed that NiPdAu resulted in minimum IMC growth. While NiAu saw IMC grown in selective IMC grains, OSP, SOP and ImSn saw significantly growth in IMC.

7. IMC sees strong growth in OSP, SOP and ImSn under temperature cycling or thermal ageing because no diffusion barrier such as Ni is there between copper and solder. Devices using these pad finishes can have good drop test performance at time zero but might see compromised drop reliability after some use time.

8. HSSBS testing results shows that NiPdAu performed best in resistance to high strain-rate impact loading with no IMC failure for both time zero and 1000 hours aged samples. NiAu ranked second to NiPdAu. SoP saw most brittle IMC failures in both time zero and thermal aged samples.

9. It is observed from this HSSBS test that no direct correlation from failure mode percentage and drop test results
is found. However, the HSSBS test does help us to evaluate the ageing effect on failure mode. Most importantly, NiPdAu is found in this study to show excellent resistance to high temperature ageing.

Acknowledgments
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