“Study of Pd Mixing During Pd-Cu Wire Ball Formation and Impact on Wire Bond Quality”

by

Flynn Carson
STATS ChipPAC Inc., 47400 Kato Rd, Fremont, CA 94538
flynn.carson@statschippac.com, 510-979-8338

Jae Hak Yee, Soo San Park
STATS ChipPAC Korea Ltd.
jaehak.yee@statschippac.com, soosan.park@statschippac.com

Edward Fontanilla
STATS ChipPAC Singapore Ltd
edward.fontanilla@statschippac.com

Copyright © 2012. Reprinted from 2012 Electronic Components and Technology Conference (ECTC) Proceedings. The material is posted here by permission of the IEEE. Such permission of the IEEE does not in any way imply IEEE endorsement of any STATS ChipPAC Ltd’s products or services. Internal or personal use of this material is permitted, however, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or distribution must be obtained from the IEEE by writing to pubs-permission@ieee.org.

By choosing to view this document, you agree to all provisions of the copyright laws protecting it.
Study of Pd Mixing During Pd-Cu Wire Ball Formation and Impact on Wire Bond Quality

Flynn Carson
STATS ChipPAC Inc., 47400 Kato Rd, Fremont, CA 94538
flynn.carson@statschippac.com, 510-979-8338

Jae Hak Yee, Soo San Park
STATS ChipPAC Korea Ltd.
jaehak.yee@statschippac.com, soosan.park@statschippac.com

Edward Fontanilla
STATS ChipPAC Singapore Ltd
edward.fontanilla@statschippac.com

Abstract

The skyrocketing price of gold has driven the rapid adoption of copper wire in semiconductor packaging. Cu wire is being used for increasingly advanced applications requiring copper wire bond to finer bond pad geometries and structures. Palladium coated Cu wire (Pd-Cu wire) has emerged as the preferred material to realize the cost benefits of Cu wire while achieving the same yield and reliability levels as Au wire. However, during the ball bond formation, the Pd-Cu wire is melted causing mixing of the Pd and Cu. This paper presents the results of a fundamental study of Pd-Cu wire mixing during the ball formation process. An Electronic Flame Off (EFO) process is used to form the ball. Pd mixing in the ball due to the EFO condition is studied. Visual appearance and quality of the ball will also be evaluated. Several bonding wires suppliers are analyzed. Resultant hardness of formed ball is measured. The impact on the stability of the bonding process to the aluminum bond pad is studied, including analysis of the bond interface and Al splash during bonding. Through this study fundamental insight into the variability of Pd mixing and appearance in formed ball related to wire supplier and EFO parameter is gained.

Introduction

Cu wire is being rapidly adopted to reduce the packaging cost of wire bonded consumer, communication, and computing devices [1]. Adoption is across all wire bond package types, both leadframe and laminate substrate based. The maturity of Cu wire has improved such that it is now being introduced for more demanding applications, including automotive. The type of Cu wire predominantly used in production today for IC devices is Pd coated Cu wire or Pd-Cu wire. Pd-Cu wire is manufactured with a very thin layer of Pd (about 100nm or 2% by weight) on the Cu wire surface. This helps prevent oxidation of the Cu wire in the production environment and has been shown to improve process window and reliability [2, 3, 4, 5]. Many bonding wire suppliers now offer Pd-Cu wire. Most suppliers claim some special knowledge or manufacturing process that differentiates their wire. During wire bonding the ball bond, or Free Air Ball (FAB), is formed with Electronic Flame Off (EFO) and mixing of the outer Pd layer and inner Cu wire occurs. A reported advantage of Pd-Cu wire is that consistent ball formation can be achieved using nitrogen (N₂) gas instead of forming gas (5%H₂:95%N₂) [6, 7]. There is still relatively little data to date regarding how the key factors such as EFO parameter, gas type, wire supplier, and Pd thickness influence the Pd mixing, visual quality, hardness and subsequent bondability of the FAB to IC device with aluminum bond pads. This paper will show the results of such study for Pd-Cu wire offered by several different suppliers.

EFO Parameter Effect

For the purpose of this study a Kulicke & Soffa (K&S) Industries IConn wire bonder configured with Cu wire bonding kit was used. Either forming gas or N₂ gas can be inputted into the machine to create the atmosphere in which the ball is formed. The flow of this cover gas can impact the ball formation. For the purpose of this study this gas flow has been fixed at a level between 0.5 to 0.7 liters per minute which is recommended by the equipment manufacturer and also confirmed by our internal evaluation. EFO current and time settings determine the FAB size. FAB size is optimized based on the applicable IC device bond pad opening and wire diameter required. Original wire diameter chosen for this study is nominally 20µm and target FAB size is 50% larger than the original wire diameter (30µm). Four different wire suppliers are evaluated as part of this study. The Pd percentage by weight for each wire supplier was checked to be within a range of 2% to 2.4% for the purpose of this study. These wire suppliers and respective products evaluated are all qualified and in production today.

In the first evaluation we analyze the effect of EFO current on the FAB size using forming gas. Figure 1 shows the result of the analysis. The four different wire suppliers are labeled A, B, C, and D. EFO parameters (current, time) are set at three levels: Low (60mA, 186µsec), Medium (90mA, 110µsec), and High (120mA, 76µsec). The bonding machine automatically calculates the EFO time for a given current setting to achieve the targeted FAB size for a given wire diameter. Initial measured diameter of each supplier’s wire is about 100nm or 2% by weight. Four different wire diameters are noted in the figure (varies from 19.27 to 19.81µm).
relationship to the wire supplier. There is less variation of FAB size between the suppliers with medium and high EFO current. Wire B exhibits lowest standard deviation at low EFO setting, whereas Wire D shows lowest standard deviation at high EFO setting. This analysis shows the importance of optimizing the EFO parameter to get the targeted FAB size and the need to confirm by measurement. Cannot assume will get same FAB size for same EFO condition across Pd-Cu wire suppliers.

Figure 1: FAB diameter per EFO current and wire supplier (forming gas)

FAB visual quality is also an important consideration. Inspection of 100 specimens per leg for any visual defect such as abnormal FAB shape, dimple, or oxidation was performed and results are in Figure 2. Wire D showed best result with no abnormalities detected and Wire C showed the most abnormalities, but these defects are considered acceptable for a stable production bonding process, there were not gross defects.

Figure 2: FAB visual quality per EFO current and wire (forming gas)

Pd coverage or distribution on the FAB surface was also analyzed for each leg (sample size 30 FAB per leg). An image of FAB is captured and analyzed to determine percentage of Pd coverage on FAB surface using automated methodology developed by our company. Results (Figure 3) show Pd coverage is improved and shows less deviation as the EFO current setting is increased. Wire B is exhibiting significantly higher coverage of Pd with higher EFO setting. The other wires show less incremental increase with higher EFO setting and Wire D shows the least amount of Pd coverage and incremental increase. Wire A and B show lowest standard deviation regardless of EFO setting, indicating very repeatable Pd distribution and stability.

Figure 3: FAB Pd coverage per EFO current and wire (forming gas)

Formed balls were also cross sectioned in this evaluation to determine the distribution of the Pd within the ball for each leg as well as to measure the hardness. Five balls were cross sectioned for each leg. A representative cross section for each leg is shown in Figure 4. Wire B shows more Pd distributed within the FAB, whereas Wire A, C, and D show the Pd mostly distributed at the periphery of the ball. Figure 5 shows the result of Vickers hardness measurement done at one point within each of the five cross sections per leg (sample size 5 measurements per leg). A bare Cu wire Vickers hardness measurement is added to each EFO current setting for reference. General trend shown is that the hardness is decreasing with higher EFO current for Wire A, C, and D, but for Wire B the hardness is increasing instead. This corroborates the observation from Figure 4 that Wire B has more Pd distribution or mixing, and hence higher hardness, within the FAB due to increased EFO current. High standard deviation of hardness for Wire B with increased EFO would logically correlate to more heterogeneous mixing. Wire D has the lowest hardness regardless of EFO current setting and appears to have the least amount of Pd mixing within the ball (based on Figure 4), such more homogeneous composition would correlate to the lower standard deviation exhibited.
This analysis is supporting the claim of wire suppliers that their formulation and manufacturing process can influence the Pd coverage, distribution within the FAB, and hardness.

This EFO parameter study shows that not all Pd-Cu wire is created equal. There are subtle differences that influence the FAB size, visual quality, Pd coverage and distribution, and hardness per EFO setting. Most noteworthy is Wire B exhibiting a different trend than other wires (higher Pd mixing and hardness) as EFO current increases. Also, targeted FAB size should be verified as it can vary with supplier.

**Gas Type Effect**

The analysis so far has focused on FAB formation in forming gas. However, a marketed advantage of Pd-Cu wire is that it is less sensitive to oxidation and hence readily available and economical. \( \text{N}_2 \) gas can be used for ball formation. The impact of using \( \text{N}_2 \) gas instead of forming gas on the FAB size can be seen in Figure 6. The forming gas data shown for comparison is the same as in Figure 1. There is not much difference in average FAB size due to nitrogen gas, especially with medium and high EFO current, regardless of wire supplier. For low EFO setting, higher variation of FAB is observed between wire suppliers, especially for Wire C and D. Nitrogen gas exhibits more consistent FAB size and less standard deviation regardless of wire supplier or EFO condition.

Figure 7 shows how the visual quality is impacted by switching to \( \text{N}_2 \) gas. There is a marked increase in the number of abnormal FAB for each wire supplier. In the case of Wire C, the number of abnormalities represents over 70% of the sample size. Wire D is the least impacted by the change to \( \text{N}_2 \) wire and has the least observed abnormalities regardless of gas type. Any abnormality is noted here in this study and they may not cause production defect or yield loss, but it is an indication that some wire supplier is much more prone and sensitive to producing such anomalies during ball formation and that this sensitivity is increased when using \( \text{N}_2 \) gas as opposed to forming gas.

**Gas Type Effect**

The effect of \( \text{N}_2 \) gas on FAB Pd coverage was measured and result shown in Figure 8. The same trend of increased Pd
coverage of FAB with increased EFO current is seen for N₂ gas. However, there is a marked difference between Pd coverage for N₂ gas compared to forming gas, the Pd coverage is less with nitrogen gas, especially at low EFO current and this difference varies by wire supplier. Wire A shows much lower Pd coverage than other wire suppliers, the difference being more pronounced at lower EFO setting. By contrast, Wire D shows relatively little difference due to nitrogen gas, even at low EFO setting.

Using nitrogen gas instead of forming gas leads to less variation of FAB size and standard deviation per EFO setting, but more visual abnormalities are observed, as well as less Pd coverage. Again, the effect of nitrogen gas varies by wire supplier and such differences are more pronounced at lower EFO setting.

Pd Thickness Effect

Care was taken to assure that almost the same Pd thickness was provided from the different wires used for the previous evaluation. In production, this thickness can vary due to wire process variation and can be skewed towards limits of specification range. Pd thickness translates into a difference in the weight percentage of Pd. Pd layer thickness is typically specified such that it can vary within 1.5% to 3.1% by weight (which roughly translates from 70nm to 130nm thickness). To study the effect of Pd thickness, Pd-Cu wire with 1.5%, 2.1%, and 3.1% by weight of Pd was obtained from Wire Supplier A. Figure 9 shows the results of FAB diameter study with different Pd % by weight and setting the EFO current to 60mA, 90mA, 120mA levels as in previous studies. Forming gas was used. The results show that higher Pd content has a tendency to produce a smaller FAB and lower standard deviation. FAB size difference is less pronounced at high 120mA EFO setting. However, the predominant trend is similar to Figure 1 and 6, in that the FAB size decreases with EFO current increase, regardless of Pd content.

Figure 9: FAB diameter per Pd% by weight and EFO current (forming gas)

<table>
<thead>
<tr>
<th>EFO</th>
<th>L(1.5%)</th>
<th>M(2.1%)</th>
<th>H(3.1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60mA</td>
<td>32.97</td>
<td>33.09</td>
<td>32.12</td>
</tr>
<tr>
<td>90mA</td>
<td>32.7</td>
<td>31.02</td>
<td>30.72</td>
</tr>
<tr>
<td>120mA</td>
<td>30.21</td>
<td>29.37</td>
<td>29.96</td>
</tr>
<tr>
<td>Avg</td>
<td>32.97</td>
<td>33.09</td>
<td>32.12</td>
</tr>
<tr>
<td>Std</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Max</td>
<td>34.4</td>
<td>34.4</td>
<td>32.6</td>
</tr>
<tr>
<td>Min</td>
<td>30.8</td>
<td>30.8</td>
<td>31.0</td>
</tr>
</tbody>
</table>

Figure 10: FAB visual quality per Pd% by weight and EFO current (forming gas)

<table>
<thead>
<tr>
<th>EFO</th>
<th>L(1.5%)</th>
<th>M(2.1%)</th>
<th>H(3.1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60mA</td>
<td>85%</td>
<td>85.9%</td>
<td>88.4%</td>
</tr>
<tr>
<td>90mA</td>
<td>90.1%</td>
<td>90.9%</td>
<td>91%</td>
</tr>
<tr>
<td>120mA</td>
<td>92.9%</td>
<td>93.1%</td>
<td>92.8%</td>
</tr>
<tr>
<td>Avg</td>
<td>85%</td>
<td>85.9%</td>
<td>88.4%</td>
</tr>
</tbody>
</table>

Figure 11: FAB Pd coverage per Pd% by weight and EFO current (forming gas)

Pd thickness impact on FAB visual quality was inspected (Figure 10). Slightly higher incidence of abnormality was seen with thicker Pd, but this is a very low level and not significant. There was no abnormality observed at high EFO setting. Again, these abnormalities are minor and would not lead to production yield loss.

Pd coverage of FAB was also studied (Figure 11). There is higher Pd coverage due to thicker Pd, but the difference is not pronounced (within a few percent). Again the overriding trend is increased Pd coverage with increased EFO current setting. Also, the standard deviation is decreasing with increased EFO. The impact of Pd thickness on FAB Pd coverage is most evident at low EFO setting, but even here the average range is 3.4% and absolute range is about 10%.

The overall impact of Pd thickness on FAB size, visual quality, and Pd distribution is not very significant if forming gas is used as in this study.

Bondability Study

The evaluations performed have focused on the ball formed, but not on the bonding of such ball. Will these reported differences in FAB size, Pd distribution, and hardness with different wire suppliers translate to meaningful differences in bond formation and quality? In order to answer this question, two legs were prepared for bonding evaluation. These legs were selected to bracket or represent the corners of the observed FAB results (with forming gas). Wire B with High (120mA) EFO setting was selected to represent “high hardness and Pd mixing” (Leg 1). This combination produced the highest hardness (91.03 HV), Pd coverage (98.8%), and
observed Pd mixing or distribution within the FAB. Wire D and Low (60mA) EFO setting was selected to represent “low hardness and Pd mixing” (Leg 2). This combination produced low hardness (78.5 HV), lowest Pd coverage (83.6%) and low observed Pd mixing within FAB.

The bonding was done on a 45nm wafer fabrication node device with Circuit Under Pad (CUP) bond pad structure, 43μm bond pad opening, and 1.45μm Al thickness on bond pad. Bonding capillary with 1.0 mil hole diameter, 1.2 mil chamfer diameter, 3 mil tip diameter, 0.3 mil outer radius, and 11° face angle was used. Bonding parameters already optimized and qualified for this device were applied to both legs. Post bond Al thickness remaining, Al splash, Ball Aspect Ratio (BAR), Ball Shear Test (BST), Bond Pull Test (BPT), Inter-Metallic Compound (IMC) coverage, and bond pad cratering output responses were measured and compared.

Cross section of 30 bonds per leg was done to measure Al-splash and BAR. Figure 12 shows almost identical results between the two legs. Remaining Al thickness is over 30% of the original bond pad thickness of 1.45μm, which is a desirable result. Leg 2 with lower hardness shows slightly more Al thickness remaining on left and right side of the bond than Leg 1. Figure 13 is showing the BST and BPT comparison. Again, the result is almost identical, which can be expected because these tests are mostly dependent on the bonded ball size and area, which is almost same in this case, only a severe bonding issue would show significant difference in test result. The IMC coverage measured for five samples per leg also has practically identical result and very high average IMC coverage of 95% (Figure 14, the green highlighted area represents no IMC in this area). Cratering check is good, so there is no damage to underlying bond pad structure (this was also observed in cross section).

This evaluation indicates that the difference in bond-ability of these Legs is almost non-existent. Both of these Legs far exceed bond quality specifications and will have no issue passing customer reliability tests based on previous experience. Perhaps Leg 2 may be slightly better for very challenging applications with minimal Al bond pad thickness or delicate bond pad structure.

Figure 12: Post bond Al thickness, Al splash, and BAR

Figure 13: BST and BPT

Figure 14: IMC and cratering

Conclusions

The effect of EFO parameters on FAB size, visual quality, Pd coverage and distribution, and hardness can vary by wire
supplier and gas type. There seems to be truth in the wire suppliers claims of differentiation. In general, middle or high EFO current setting is decreasing the variation in FAB size and Pd distribution, but can increase the variation in hardness. Forming gas is recommended to improve the visual quality and improve the Pd coverage. Higher Pd thickness shows some slight improvement in Pd coverage and standard deviation, but does not seem to be a significant factor, which indicates that supplier variation in Pd thickness within specification will not make any noticeable difference. Comparison of wire bonds formed to device bond pad with High versus Low Pd distribution and FAB hardness do not show any appreciable difference except for some small difference in Al remaining on bond pad for the softer FAB. Both show extremely good bond results in this study.

The key learning in this study is that there are differences in the wire suppliers. The differences are summarized on Table 1. For sensitive or fragile bond pad, Wire D may have better process window due to softness. Wire A is a good all around performer. Wire B would be most suitable if low EFO current setting is used because it has stable FAB size and distribution. This fundamental insight is useful to determine what is important when selecting wire supplier and optimizing the wire bond process for any IC device. Future work with wire suppliers, including reliability studies, to determine best wire properties and attributes for more advanced applications and wafer fab nodes is planned.

**Acknowledgments**

The Copper Wire Engineering (CWE) group within STATS ChipPAC Ltd., led by Hon Sang Lew, played a key role in supporting the fundamental work required for this paper. Also would like to highlight the contributions of Luke Goh, Chee Keong Chin, Jeffrey Punzalan, and Pradhap Sadasivan from the CWE organization for helping enable this work.

**References**


<table>
<thead>
<tr>
<th>Supplier</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAB size</td>
<td>★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Visual quality</td>
<td>★★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
</tr>
<tr>
<td>Pd distribution</td>
<td>Surface</td>
<td>★★★</td>
<td>★</td>
<td>★ ★</td>
</tr>
<tr>
<td></td>
<td>X-section</td>
<td>Outer</td>
<td>Inner</td>
<td>Outer</td>
</tr>
<tr>
<td>Hardness</td>
<td>★★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
</tr>
</tbody>
</table>

**Table 1: Wire supplier summary**

- **Best**: ★★★
- **Good**: ★★
- **So-so**: ★
- **No good**: ∙

**Standard of score:**
- FAB size: low deviation, Visual quality: number of better shape, Pd distribution: High Pd %, Hardness: soft