Challenges and Resolution of Insulated PdCu Wire Bond for TBGA HVM Robustness

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Abstract
Insulated wire bond is getting more attention nowadays by packaging technologist as another potential option of cost saving after Cu wire bond conversion due to its flexibility in wire bond without the fear of wire short. The process offers greater flexibility in wire bond layout design which can lead to die size reduction and standardization of substrate / leadframe for cost saving. As the wire has the capability to touch each other without causing electrical short, this feature also has been adopted to generate or enhance the capacitance effect based on device requirement.

Insulated wire bond process however has many challenges to overcome as compared to the bare wire bond process. With additional insulation organic wire coating, direct contact of 2 metals, wire and Al pad for IMC formation is not possible. Organic coating needs to be sufficiently removed for inter diffusion of 2 metals. The challenge can be easily observed during post bond formation with severe wire bond problems such as non stick on lead (NSOL) and short tail if the wire coating is not effectively eliminated through mechanical scrubbing. Ball bond process, with the existence of electrical flame off (EFO) to burn and evaporate organic coating before free air ball (FAB) formation, is a relatively easy process for insulated wire, but thicker insulation coating can result in pointed or irregular FAB formation resulting in non stick on pad problem in some severe cases.

This study aims to define an optimum wire bond process and coating material recipe for Tape Ball Grid Array (TBGA) package with first ever attempt at using 18µm PdCu wire size to achieve high volume manufacturing (HVM) capability for 47µm pad pitch. TBGA is well known for its difficulty on post bond formation due to fine pitch lead finger on polyimide flex sitting on top of adhesive layers in substrate configuration. The characterization and optimization process involved 4 key factors: capillary, plasma cleaning, wire coating and wire bond parameters. Series of evaluation and DOEs were performed to establish optimized parameter window on each factor in terms of wire bond integrity and bondability. All optimized settings were later integrated and subjected to HVM run. From HVM verification, all wire bond quality requirements were fulfilled. Wire bond MTBA achieved more than 2hrs and successfully passed industrial level package reliability stressings with no electrical failures. In summary, the most challenging 18µm insulated Pd Cu wire bonding process on TBGA package can be made possible through a detailed process characterization and careful consideration of manufacturing performance.

1. Introduction
Insulated wire bond was introduced since 2005 with gold wire. The main purpose is to prevent wire short due to increase in wire count couple with the reduction of wire pitch, especially on high pin count ball grid array package. Higher wire cost due to additional coating process is the main reason the product was not popular in the semiconductor packaging industry. However, after wide spread copper wire bond adoption , insulated wire bond was getting more attention by packaging technologist as another potential cost saving catalyst. Wire bond yield improvement, for example, is another main focus after packaging cost reduction. A device that suffers wire short due to high wire count or designed with a wire bond process design rule limit has the opportunity to achieve higher wire bond yield and greater design option with the use of insulated wire. Due to flexibility in wire bond without the fear of wire short, insulated wire offer total flexibility in wire bond layout design [1] which leads to die size reduction as bonding pad no longer require to locate at the peripheral edge of the die. At the same time, array wire bonding from insulated wire bond process also provides flexibility in substrate and leadframe design which in return, the standardization of substrate / leadframe and thus the reduction of tooling cost investment. Besides cost saving benefits, development is also currently ongoing to assess insulated wire technology possibilities to improve device electrical performance. As the wires have capability to touch each other without causing electrical short, this feature has been adopted to generate or enhance the capacitance effect based on device requirement as shown in Figure 1.
2. Process Challenges

With the additional insulation organic wire coating, direct contact of 2 metals, wire and Al pad metal for IMC formation is not possible and thus inhibits a good bond formation. The contact area between the wire and lead is only at the second bond tail area or the edge of crescent causing weak post bond. The study shows a basic bonding with insulated Au wire yields lower stitch pull force than the bare wire. [2] The reduction is even more with the use of harder wire such as Cu or Pd Cu wire. Study also shows no cracking in coating material at the center of the deformed area. [3] Stitch pull strength comparison of 18µm insulated Pd Cu wire and Pd Cu wire are shown in Figure 2 which indicate the stitch pull strength for insulated Pd Cu wire is significantly lower as compared to non-insulated Pd Cu wire. A special movement of the capillary to enable a mechanical abrasion was able to improve the stitch pull strength further. These involved the use of special heavy matte finish capillary tip surface design to enable effective tearing of the wire insulation at second bond [4]. The excessive mechanical abrasion, however introduces relatively unstable 2nd bond tail cutting process resulting in premature wire tail cut and thus shorter or no tail length for next EFO wire bond cycle. Post bond process window for insulated wire therefore is narrower compared to bare wire: milder post bond parameter settings may result in NSOL problem due to insufficient IMC formation with the presence of excessive organic coating. Stronger post bond parameter settings on the other hand, results in short tail or EFO open problem due to premature tail cut. Unoptimized process induces excessive wire bond process stoppages or lower mean time between assists (MTBA) problem in addition to other manufacturability issues. Initial wire bond MTBA assessment for un-optimized insulated Pd Cu process showed unacceptable MTBA which is far below the MTBA target as shown in Figure 3. Detailed breakdown of wire bond stoppages showed 83% of the stoppages are post bond related: 78% related to short tail and 5% related to NSOL as shown in Figure 4.

For first bond formation, organic coating is burnt and evaporated during EFO firing, producing FAB that are similar to bare wire for subsequent ball bonding. The coating thickness variation as well as tail length consistency, however can affect FAB shape and consistency which can lead to off-center ball, ball size variation or non stick on pad problem. Hence, insulated wire bond process requires proper optimization on ball bond, post bond and FAB formation. Otherwise, one might expect a lower wire bond...
yield and MTBA process as compared to bare wire. As shown in Figure 6, an unoptimized 18µm insulated Pd Cu wire bond yield is about 1.0% lower compared to Pd Cu wire.

Figure 5. Insulated wire problem (a) (b) off center FAB (c) (d) NSOP due to small FAB

Figure 6. 18µm insulated Pd Cu wire and Pd Cu wire bond yield comparison.

3. Experimental Results and Discussions

This paper aimed to evaluate various insulated wire bond material and process factors: capillary, wire, plasma cleaning and wire bond process parameters. Results and conclusion from these assessments will be used to establish an optimum HVM process and more robust manufacturing window for desired production throughput, MTBA as well as reliability performance.

All experiments were performed on Freescale Tape Ball Grid Array (TBGA) package with the Hip7 wafer technology. Minimum bond pad pitch is 47µm. Insulated Pd Cu wire used in the assessment is 18µm wire size X-Pdflash wire from Heraeus. Wire bond was performed on K&S IConn LA wire bonder. TBGA is well known for its difficulty on post bond formation due to flimsy lead finger fabricated on polyimide flex tape sitting on top of 2 adhesive tapes. The selected test vehicle is TBGA 35 X 35 package with 7 wire tiers to accommodate total wire count of 965 wires, making it as one of the most stringent test vehicles for insulated wire bond development. The development process is getting tougher with the use of smaller wire diameter of 18µm size due to the requirement to achieve smaller bonded ball of 34µm.

3.1 Capillary

Capillary optimization started with the optimization of capillary dimensions. Most of the dimensions related to post bond were optimized: face angle, outer radius and tip diameter. The most prominent dimension is tip diameter. From the study, stitch pull strength can be increased and short tail problem able to reduce drastically with the increase of capillary tip diameter. Base of calculation, however, tip diameter for 47µm bond pad pitch process is not able to exceed 63µm as larger tip diameter has a higher risk to disturb the previous bonded wire. Another factor for consideration is the capillary surface morphology. Two capillaries with different tip surface finishing were tested: smoother and rougher surface to assess stitch pull strength and Cu remain % after the stitch pull test. Based on the results, rougher tip surface capillary able to improve 18% stitch pull strength as compared to smooth tip surface capillary as shown in Figure 7. At the same time, Cu remain % is higher for sample bonded with rougher tip surface capillary as shown in Figure 8. Rougher surface capillary was later subjected to volume sample wire bond assessments. From the initial study, the capillary was not able to achieve targeted capillary touchdown limit. Fresh capillary need to be replaced to continue the wire bond process due to excessive short tail problem. Analysis on used capillary surface observed excessive foreign matter build up on the capillary wall as shown in Figure 9. EDX analysis indicates the deposited material is similar to organic material. So, it is believed that part of the organic coating which evaporated during EFO firing was deposited on capillary wall. To resolve this problem, tail length setting was increased in order to lower down the EFO fire level to be away from capillary tip. Tail length setting, however need to increase with caution as too long of tail length can result off center bonded ball problem.

Figure 7. Rough and smooth tip surface capillaries stitch pull strength comparison.
3.2 Wire Coating Process

Wire coating has very crucial effect on the bondability of insulated wire. A lot of wire coating factors need to be carefully tailored in order to establish a stable, problem free, reliable insulated wire bond process: coating thickness, thickness consistency, coating ductility and the interaction with wire metal. An assessment was performed to study the effect coating thickness on FAB formation. From the assessment, pointed and irregular shape of FAB was observed in the un-optimized coating wire sample as compared to optimized coating wire sample. The FAB SEM images are shown in Figure 10. Many wire manufacturing process factors were considered in the DOE to establish a wire bond friendly coating characteristic: coating material, annealing condition, coating curing temperature, coating speed, coating die size, etc. Series of DOE was performed and 4 different coating processes were finalized and subjected to wire bond evaluation. From the evaluation, process D has the best average stitch pull strength compared to other 3 processes as shown in Figure 11. Process D also showed the lowest stoppages as compared to other wire samples. As such, process D was selected for wire coating process. Besides, wire floor life characterization is another important wire assessment to determine the duration of the best wire condition for better bondability and process manufacturability. In the assessment, wire sample was staged on wire bonders at clean room environment to simulate actual wire bond manufacturing process. Both stitch pull strength and wire bond stoppages were monitored during the assessment. As shown in Figure 13, stitch pull strength decreased with the increase of staging duration. After 10 days, minimum stitch pull strength dropped below the spec limit of 2gm. As for wire bond MTBA monitoring, drastic increase of wire bond stoppages due to short tail was observed after 9 days of wire staging. When the MTBA assessment was repeated with the aged capillary, drastic increase of wire bond stoppages occurred earlier after day 7 which indicates both wire floor life and capillary touchdown have an adverse effect on the bondability of insulated Pd Cu wire. Based on the assessment, wire floor life of insulated Pd Cu was set to max 6 days, which is similar to current bare Cu wire floor life control.
Figure 12. Cu remain after stitch pull (a) process A, (b) process B, (c) Process C, (d) Process D.

Figure 13. Stitch pull strength versus wire floor life

Figure 14. Short tail occurrence versus wire floor life for both fresh and aged capillaries (note: to remove the Y-axis values)

3.3 Plasma Cleaning

Plasma cleaning also plays an important role to allow better wire bond manufacturability by providing a cleaner bonding surface for sensitive wire bond processes such as insulated wire bond. Evaluation has been conducted on 4 different microwave plasma settings with different plasma gas flow and process time. Wire bond sample went through each plasma cleaning setting and subjected to wire bond process verification after that. Two wire bond parameter settings were used to evaluate the plasma performance. Based on evaluation results, plasma process with both oxygen and argon gases and prolonged plasma time has better performance in both stitch pull strength and wire bond MTBA as shown in Table 1 especially for wirebond parameter 1 that is optimized. Another plasma cleaning assessment was performed mainly comparing the Argon gas effect with 2 different flow rate settings. Through SEM inspection, smoother bond finger surface topography was observed on bond finger that went through recipe 1 plasma cleaning while tiny bumps was observed in recipe 2 sample as shown in Figure 15. When subjected to stitch pull test, sample with recipe 1 cleaning achieved higher stitch pull strength, about 16% higher as shown in Figure 16.

Table 1. Stitch pull strength and wire bond stoppages for various plasma settings

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<tr>
<th>Plasma</th>
<th>Stitch Pull Avg</th>
<th>Wire Bond Parameter 1</th>
<th>Wire Bond Parameter 2</th>
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<td>NNC 3</td>
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<td>0</td>
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<tr>
<td></td>
<td>Short Tail</td>
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<tr>
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<td>0</td>
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<tr>
<td></td>
<td>Short Tail</td>
<td>3</td>
<td>5</td>
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<tr>
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</table>

Figure 15. Substrate bond finger surface condition after plasma (a), (b) recipe 1 plasma (c),(d) recipe 2 plasma

Figure 16. Recipe 1 and recipe 2 plasma stitch pull strength comparison
3.4 Wire Bond Parameter.

With additional insulation coating layer, wire bond process is rather complicated as compared to bare wire. The coating needs to be scrubbed off for wire metal exposure before continuing with the standard wire bond process. Therefore, wire bond process involves 3 main stages: coating break & scrub off, wire bond and tail break. For K&S bonder, the multi step process was carried out through the optimization of multi segmented pre stitch post bond parameters. The optimization started with 3 segmented settings and gradually evolve to final settings of 5 segmented process. In this 5 segmented process, 1st segment is a contact phase to scrub off wire coating layer, 2nd & the 3rd segments is a bonding phase that continue further scrubbing and initiate wire bonding process at the same time, the 4th segment contains a double skid process to enhance wire bonding and final 5th segment is tail breaking phase to ensure smooth tail formation process. Through a series of wire bond process optimization, a process was developed to suit flimsy bond finger lead condition on TBGA substrate.

3. Process & Reliability Verification

With the implementation and integration of all optimized factors of capillary, plasma cleaning, wire and wire bond process parameters, 3 wire bond settings, which representing high, low and nominal settings of the derived wire bond process window were verified. On stitch pull strength monitoring, all settings were able to exceed the min stitch pull strength of 2gm. When subjected to thermal aging of 4.5hrs at 225°C, it was observed that average stitch pull strength increased for about 24% as shown on Figure 17. This indicates that the stitch pull strength of an insulated wire increase with heat treatment. At the same time, MTBA monitoring on 2 wire bonders showed the average MTBA were able to meet target. The average MTBA after process optimization is 3.8 times higher compared to the process before optimization as shown in Figure 18. At the same time, average wire bond yield increases 2.2% with the implementation of new optimized parameters as shown in Figure 19. The optimized process also guarantees higher capillary touchdown with a 66 % increase on average capillary touchdown as shown in Figure 20. All TBGA insulated wire bond samples also passed various industrial level package reliability stresses such as temperature cycle, high temperature storage life, temperature humidity bias etc From reliability assessment, there were no wire bond related failure detected for all the stress readpoints as shown in Table 2.
4. Conclusions

Insulated Pd Cu wire bond is a newer technology for current semiconductor industry. It is a more challenging process compared to bare Pd Cu wire as the overall process window is relatively smaller. Development work was, however successfully performed with finer wire size of 18µm diameter on ultra fine pitch TBGA 47µm BPP device which is well known on post bond difficulty due to flimsy bond finger lead. Through a series of evaluations and process material optimizations on all wire bond factors, a right combination and workable process window was derived and qualified. The verification results showed the established window is feasible for high volume manufacturing run with good wire bond integrity under various industrial level package reliability stresses. The optimization work however is not ended. Continuous monitoring and improvement should be carried out at all process steps from wire manufacturing to semiconductor wire bond process to ensure insulated Pd Cu process fulfills the increasing demand on yield, MTBA and reliability requirements.

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References