Copper Power Pad Design Challenges for Robust and High Energy Efficient Packages

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Abstract

Current technology trend demands not only for high efficiency but also for portable devices, devices which can be carried and access anywhere and everywhere. This continues drives semiconductor’s package towards miniaturization. One way is by placing active circuitry underneath the bond pads, this will reduce the die size, hence achieve lower cost per chip. This technology has led to the development of a more robust top metal that can withstand the high ultrasonic energy being applied in the bond pad. The use of thick copper power metallization in package design had shown significant benefits over the conventional aluminum top metal.

Copper power metallization is a stack layer of thick copper (10um), nickel (2.0um) and gold (0.5um) plated over the top passivation layer. These prominently improve the overall device electrical performance with higher efficiency and lower Rs(on) by offering metallization with lower resistance and enables die size reduction of 10~25% and provides flexibility which allows assembly of thicker bonding wires for high power applications.

In copper power metallization, it helps in bondability and improves structural robustness especially with copper wire for underlying circuitry during the process. This paper presents the unique structure of this pad metallization, the challenges from die design phase and also looked at potential issues concerning passivation cracks and pad corrosions. This paper will also tackle how a stack layer of CuNiAu mitigates issues which are commonly encountered with Cu-Al bonding system (aluminum splash out issue, pad cratering and galvanic corrosion).

The overall component interface integrity for this new metallization is unknown to us. Detail simulations were carried out to understand the system stress generated between the copper power pad and silicon (Si) die which affect the passivation integrity as well. Detail characterizations will be discussed to understand the ratcheting mechanism and its resolution. Assessment on package integrity with Moisture Level Sensitive (MSL1) condition was done to ensure it is well integrated with currently assembly process and material used with no delamination found.

I. Introduction

In the recent years, rapid growth in electronic technology has actuated the IC (Integrated circuit) package development towards a more challenging path. IC packaging is in the trend of miniaturization, higher reliability and cost competitive.

Copper wire has drawn industry’s attention in wire bonding assembly replacing gold wire due to lower cost with better thermal and electrical performance. Nevertheless, the main drawbacks of copper physical properties are its higher hardness and vulnerability to oxidation. This raises few major issues like pad cratering, aluminum splash out and lifted bond. Reliability issues especially with circuit under pad design and low k material is of great concern.

Several research works has been carried-out to study different bond pad structure design that would be physically robust. Like the study of Hunter et. al [1] it discussed how harsh wafer probe and harsh wirebonding affects the traditional bond pads, it states that in order to have a physically robust pads, SiO2 should be protected from bending significantly during pad stress. This can be done by preventing Al deformation beneath SiO2. Several suggestions were cited that will serve as a design rule, one is when designing, lowering the metal pattern density in the metal sub-layer beneath the pad window. Limit the maximum allowed metal width or distance between spaces, slots or holes in the metal sub-layer beneath the pad window, with most restrictions imposed in MT-1. Not allowing vias beneath MT-1 and MT-2.

Further study on different bond pad stack from Bob Chylak et. al.[2] states that the use of Ni base bond pad will be desirable to protect the underlying structures. Nickel, with hardness 50% and 70% higher than Cu and Au, respectively, is receiving predominant alternative to aluminum metalization. Typically, 1um to 3 um thickness is deposited on Al or Cu base metallization. However, as a thin oxide rapidly forms on Ni, a thin noble layer of Au and/or Pd should be used on top of Ni. The combinations of NiAu, NiPdAu, NiPd structures have been matured and have been used in many semiconductor or electronic application.

Copper power metallization is one new solution for device performance especially in power packages. It is a metallization where a stack layer of copper, nickel and gold (CuNiAu) is plated over the final passivation layer with aluminum top metal. Fig.1 illustrated a typical copper power metallization compared to standard aluminum metallization.

![Copper Power Pad Design Challenges for Robust and High Energy Efficient Packages](image)

Fig.1: Comparison between copper power metallization and standard aluminum metallization

Advantages of this new bond pad technology over the traditional Aluminum bond pad were known and discussed, on the other hand, the challenge that goes along from the development of this new structure up to the assembly site were seldom mentioned. In this study, the effect of each process assembly will be discussed and how...
2. Methodology, result and discussion

One of the key challenges for copper power pad metallization is the system stress generated due to mismatch between the coefficients of thermal expansion (CTE) of copper power pad and silicon (Si) die which affect the passivation integrity. With TiCu as initial UBM, the overall component interface integrity is yet to be known.

Detailed characterizations were executed to understand the ratcheting mechanism and its resolution. Assembly line process impact on crack passivation and pad corrosion drives series of improvement activities crossing over assembly site, wafer fab and global technology development group.

Assembly assessment criteria

The incoming wafers were visually inspected to check for defects related to wafer processing and back grinding. At wafer saw, a standard saw process flow was used with mixture of DI water and surfactant which will prevent the copper surface from oxidation. After saw, wafer will be washed with DI water, dried and inspected with nine-point inspection across the entire wafer surface.

During assembly process, the wafer or sawn units were subjected to inspection criteria as tabulated in Table I with a predefined sample size.

<table>
<thead>
<tr>
<th>Inspection criteria</th>
<th>Assembly process</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Checking for passivation crack</td>
<td>Incoming wafer inspection</td>
<td>9 points</td>
</tr>
<tr>
<td></td>
<td>After wafer saw</td>
<td>9 points</td>
</tr>
<tr>
<td></td>
<td>After die bond oven cure</td>
<td>80 units</td>
</tr>
<tr>
<td></td>
<td>After wire bonding</td>
<td>160 units</td>
</tr>
<tr>
<td>Checking for discoloration of copper power metal</td>
<td>Incoming wafer inspection</td>
<td>9 points</td>
</tr>
<tr>
<td></td>
<td>After wafer saw</td>
<td>9 points</td>
</tr>
<tr>
<td></td>
<td>After die bond oven cure</td>
<td>240 units (1 panel of leadframe)</td>
</tr>
<tr>
<td></td>
<td>After wire bonding</td>
<td>240 units (1 panel of leadframe)</td>
</tr>
</tbody>
</table>

At die bond process, a standard oven profile for QFN with curing temperature of 175°C for 2 hours. After oven cure, inspection for passivation crack and discoloration of copper power metal was done. An evaluation prior wirebonding process was done by staging the die bonded strip for 30 minutes in the heater block with 210°C, then visual inspection. During the entire assembly process, high power scope with 200x magnification was used for passivation crack inspection. For pad discoloration, minimum 50x magnification was used. Each passivation crack location and the frequency of occurrence were mapped. The direction of crack was recorded as well.

Result of inspection

Visual inspection result shows there were 2 major issues:

1. Passivation crack after die bond oven cure propagates during wire bonding heating process.

2. Pad discoloration after die bond and after wire bonding heating process.

Passivation crack is a thermo mechanically induced failure. The yield stress of copper power metallization is a result of CTE mismatch with silicon die which initiates passivation crack. It occurs at high stress concentration point (die edge and corner region) during die bond oven cure heating process. With higher temperature during wire bonding process, copper power metallization undergoes thermal expansion and metalization cracks initiate. The cracks propagate during wire bonding heating process due to high stress concentration point. The cracks are recorded and marked on the wafer. Each passivation crack location and the frequency of occurrence were mapped. The direction of crack was recorded as well.
bonding, the cracks propagate. Passivation crack area was sent for Focused Ion Beam (FIB) cross-section. The results show the crack is terminated at Al metal layer and doesn’t propagate to active die area.

2. Copper power metal bonding pad corrosion (discoloration) after wafer saw process.

Using surface analysis with Scanning Electron Microscope (SEM) and Energy Dispersive X-ray (EDX) on both affected pad and control pad. SEM examination did not reveal any differences in texture of bond pad surface between discolored and good bond pad surface as shown in Fig.6. EDX analysis at 5kV on discolored pad revealed presence of Cu and Au while on good pad only Au was detected. Fig.7 shows the analysis result.

Fig.6: SEM analysis on the texture between discolored pad and non discolored pad.

Fig.7: EDX analysis showing present of Cu on the discolored pad.

The discoloration mechanism can be explained as by the galvanic corrosion at wafer saw process with exposed copper sidewall of copper power metalization. With reference to the anodic index table, the anodic index of Au is 0.00V, Cu is 0.35V and for Ni is 0.30V. According to literature, a difference of 0.15V and above in a harsh environment is sufficient to have galvanic corrosion between two metals. The hypothesis is that the exposed copper corrodes and migrates onto the gold layer. Series of characterization were performed at different stage of process to further understand the problem and its resolution.

**Passivation crack and pad corrosion characterization**

**Die Thermo-mechanical simulation**

As passivation cracks were observed at die bond oven cure and wirebond stage, the die, copper power metal, die-attached adhesive and flag were simulated. Mold compound, leads etc. will be added in the subsequent models when rest of the assembly stages and reliability cycles are simulated. Sub-modeling technique was carried out and result is as below.

Simulations match the location of the cracks found during assembly assessment.
From the thermo-mechanical simulation, we can conclude that: Thinner Al (1um instead of 1.5um) causes ~10% lower stress in top passivation layer. Having a 5um Ni foot on Cu layer decreased the stresses by 19%. Pullback and chamfer decrease the stresses by 6%. Shifting the Cu over Al layer only change the location of the maxima, but didn’t bring down magnitude of the stresses.

Copper power metal structure evaluation

From the inputs taken from thermo-mechanical simulation, the copper power metal structure was redesigned to reduce stresses on top passivation layer. At the same time, it aims to prevent corrosion. Four structure options have been analyzed and were summarized as below:

<table>
<thead>
<tr>
<th>Option</th>
<th>Structure</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cu</td>
<td>Lower cost, Prone to corrosion</td>
</tr>
<tr>
<td>2</td>
<td>Cu/Ni/Au</td>
<td>Higher cost, Prone to sidewall corrosion</td>
</tr>
<tr>
<td>3</td>
<td>Cu/Ni/Pd/Au</td>
<td>Higher cost, With sidewall protection</td>
</tr>
<tr>
<td>4</td>
<td>Cu/Ni/Au with sidewall protection</td>
<td>Low stress, No corrosion, Robust process</td>
</tr>
</tbody>
</table>

Option1 impedes Cu wire bonding because of exposure to corrosion while Option3 induce highest cost. For this reason, Option2 and Option4 were identified for assembly evaluation. Structurally, the difference is that Option2 will have exposed copper on the sidewall of the bond pads while for Option4 the copper sidewall will be protected with NiAu layer.

Option2 without sidewall protection showed pad corrosion after wafer saw process. And it remains in subsequent assembly processes while Option4 with sidewall protection does not exhibit any sign of pad corrosion. Option4 structure with sidewall protection helps to reduce the cracks occurrence to ~12.5% out of 80 samples inspected. Inspection shows the passivation crack with Option4 was significantly improved.

Inspection for pad discoloration and passivation crack was performed and the results were recorded.

<table>
<thead>
<tr>
<th></th>
<th>Option2</th>
<th>Option4</th>
</tr>
</thead>
<tbody>
<tr>
<td>After Wafer bond 1. No passivation crack. (0/80)</td>
<td>2. Found pad discoloration on localized single bond pad. (8/80)</td>
<td></td>
</tr>
<tr>
<td>After Wire bond 1. No pad discoloration on localized single bond pad. (8/80)</td>
<td>2. Found pad discoloration on localized single bond pad. (8/80)</td>
<td></td>
</tr>
</tbody>
</table>

Inspection Result

Fig. 9: Option2 and Option4 top view

Fig. 10: Passivation crack mapping for Option2 and Option4

Development of structure underneath copper power metal

Structure underneath copper power metal had the most influence in eliminating passivation cracks. Passivation layer must be planarized to eliminate stress concentration points. With optimized planarized passivation scheme, thin top metal and TiW as seed layer (underneath barrier layer) passivation cracks were then eliminated.
compared with the use of Ti as seed metal. It was believed that the addition of Tungsten (W) act as stress absorbing layer during the heat cycle. CTE of TiW is closer to Si (4.5ppm/°C). Besides, TiW will be helpful in Cu wire bonding to prevent potential bond pad underlayer damages. This is crucial as thicker Cu and Al wires are of big potential to be used in devices that will be design with this new technology.

Table IV: Young’s Modulus, Poisson’s ratio and CTE for different materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
<th>CTE (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>180</td>
<td>0.22</td>
<td>2.8</td>
</tr>
<tr>
<td>Ti</td>
<td>116</td>
<td>0.32</td>
<td>8.6</td>
</tr>
<tr>
<td>TiW</td>
<td>260</td>
<td>0.26</td>
<td>4.5</td>
</tr>
<tr>
<td>Cu</td>
<td>128</td>
<td>0.36</td>
<td>16.4</td>
</tr>
<tr>
<td>Ni</td>
<td>200</td>
<td>0.31</td>
<td>13.4</td>
</tr>
<tr>
<td>Glass</td>
<td>85.5</td>
<td>0.31</td>
<td>5.73</td>
</tr>
</tbody>
</table>

3. Conclusions

The introduction of copper power metallization in a high energy efficient package shows several benefits in electrical performance and package assembly process. Initial feasibility study shows two major issues with this new pad metallization, passivation crack after heating cycle and pad discoloration. Series of characterization/DOEs with engineering simulation contribute to the improvement on copper power metal layout, sidewall protected structure, planarized passivation scheme and underneath seed metal layer with TiW. All these solutions are eventually mitigate the earlier encountered issue.

An extensive reliability assessment has proven well adhesion between copper power metallization with mold compound material as no delamination after MSL1 precon. Other stress test, i.e. HTOL, HTSL, PC-HAST, PC-UHAST and PC-TC shows good implementation of copper power metallization in assembly process.

Acknowledgements

The author wish to express their gratitude to Onsemi global power metal team under leadership of Mike Seddon and TAACL for the discussion, analysis support and illustrations.

References

[8] Lecture Series on Cu Wire Bond & Packaging Interaction Technology by Tanja Braun, Stefan Schmitz; Fraunhofer IZM, Dr. Gerd Kühnlein; ESATEC, Pages 4-13 (WB session 7).

Reliability assessment

Good results were obtained with a series of improvement activities accomplished in copper power metal layout– structure design, passivation planarization scheme and underneath barrier layer. These encouraging responses enable to further evaluate the integrity of copper power pad metallization in a harsh environment.

Two different package encapsulation materials were selected for this evaluation. Copper power metal technology is yet to establish the integrity of its adhesion especially after pre-conditioning with MSL1 260C. Thus, mold compound A with known for its lower CTEs and higher adhesion strength compared with mold compound B were used. Adhesion comparison test done by mold compound supplier shows that A have higher adhesion than B at both room temperature and 260 C. The test was done on PPF frame with PMC condition 175 C/ 4 hrs.

Acoustic Microscopy Analysis revealed no delamination presence on die surface, top of flag, die attach and post/leads after pre conditioning MSL1 260C.

All the sample runs were able to pass electrical test after stress test on HTOL 1008hrs, HTSL 1008hrs, Pre Conditioning UHAST 96hrs and Pre Conditioning TC 500cyc.

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