Fabrication and Reliability Assessment of Cu Pillar Micro-bumps with Printed Polymer Cores

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Abstract—Cu pillar micro-bumps with polymer cores have been demonstrated to effectively reduce thermomechanical stress and improve joint reliability. Fabricating polymer cores by a printing approach was proposed to overcome the limitations in conventional fabrication process. Cylindrical polymer cores with diameter of 20 µm and height of 30 µm were successfully printed. Surface metallization was subsequently applied on the printed polymer cores and Cu pillar micro-bumps with printed polymer cores with diameter of 35 µm and height of 35 µm were eventually achieved. To study the reliability performance of the interconnect joints made of Cu pillar micro-bumps with printed polymer cores, flip-chip bonding technology was successfully introduced and the interconnect joints between a designed BT substrate and a silicon chip were formed. The interconnect joints made of conventional Cu pillars with identical dimensions were prepared for comparison. The reliability performance of the joints was investigated under temperature cycling condition and drop condition, respectively. Printed polymer cores increased the characteristic life by 32% in a temperature cycling test (0°C - 100°C), while the drop test showed that printed polymer cores increased the characteristic life by 4 times due to the extra compliance provided by the printed polymer cores. It can be concluded that Cu pillar micro-bumps with printed polymer cores can effectively reduce stress and improve joint reliability.

Keywords—Compliance, Cu pillar micro-bumps with printed polymer cores, interconnect joints, reliability

I. INTRODUCTION

Cu pillar micro-bumps constitute a new generation of interconnection technology for high-density fine-pitch flip-chip die stacking and 3D integrated circuit (IC) integration, that inherits the advantages from solder bumps while overcoming the drawbacks [1-6]. However, due to the significant mismatch of coefficient of thermal expansion (CTE) between the silicon chip and the organic substrate, Cu pillar micro-bumps may suffer from high thermomechanical stress during device packaging and services, which may shorten their lifespan and limit their commercialization [7-14]. Min Win Lee et al., from Amkor Technology and Fairchild Semiconductor have investigated the effect of structure and material properties on a low-k layer for flip chip packaging with Cu pillar interconnection [15]. According to finite element modeling, the stress of the low-k layer was directly related to the CTE mismatch between the die and the substrate with the maximum stress at the bump near the die corner after the flip-chip attach process. According to their model, it was noted that the Cu pillar had 20% higher stress than lead free solder and 40% higher stress than eutectic solder. Charlie J. Zhai et al., from Advanced Micro Devices studied the Cu/low-k film delamination in flip-chip packages [16]. Their modeling and experimental results demonstrated that the reduced elastic modulus of the inter-layer dielectric led to greater probability of chip-package-interaction related delamination for both failure modes, i.e. near-bump delamination and corner delamination.

Cu pillar micro-bumps with polymer cores, which provide substantial compliance, have been demonstrated by Boo Yang Jung et al., to reduce the thermomechanical stress and to improve joint reliability [17]. The polymer core was covered with a very thin Cu layer and a solder cap. The Young’s modulus of the polymer core material was much lower than that of rigid Cu, so that the bump rigidity could be reduced, while preserving the Cu pillar shape. Jung adopted finite element analysis technique to compare the stress level and reliability life cycle between the conventional solid Cu pillar bump and the polymer-cored compliant Cu pillar bump. The polymer-cored compliant Cu pillar bump reduced stress by 20% and increased solder joint lifetime by 30% under temperature cycling condition (-55°C-125°C) compared with the conventional solid Cu pillar bump.

The conventional fabrication process of polymer cores utilized the traditional semiconductor fabrication process [18-19], which suffered chip size limitation, pillar height limitation and substrate topology limitation. Adopting printing technology to fabricate polymer cores could overcome these
limitations. Polymer cores fabricated by printing technology was proposed by the authors in a previous study [20]. This paper focuses on fabrication and reliability assessment of Cu pillar micro-bumps with printed polymer cores.

II. DESIGN AND FABRICATION OF SILICON CHIP AND BISMALEIMIDE TRIAZINE (BT) SUBSTRATE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pitch (μm)</td>
<td>200</td>
</tr>
<tr>
<td>diameter of Al pad (μm)</td>
<td>70</td>
</tr>
<tr>
<td>diameter of Cu pad (μm)</td>
<td>70</td>
</tr>
<tr>
<td>diameter of oxide opening (μm)</td>
<td>50</td>
</tr>
<tr>
<td>number of bumps</td>
<td>544</td>
</tr>
<tr>
<td>chip size (mm)</td>
<td>5×5</td>
</tr>
<tr>
<td>chip thickness (mm)</td>
<td>0.525</td>
</tr>
<tr>
<td>BT substrate thickness (mm)</td>
<td>0.6</td>
</tr>
<tr>
<td>CTE of BT in XY-axis (&lt;T_g) (ppm/°C)</td>
<td>15</td>
</tr>
<tr>
<td>CTE of silicon in XY-axis (ppm/°C)</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Silicon chips and BT substrates were employed in this study because the coefficient of thermal expansion (CTE) mismatch was suitable for evaluating the compliance of the joints made of Cu pillar micro-bumps with printed polymer cores. Since the CTE of BT below glass transition temperature (T_g) in the XY-axis was 15 ppm/°C and the CTE of silicon was 2.6 ppm/°C, 12.4 ppm/°C CTE mismatch existed between the silicon chip and BT substrate. Eight daisy chain loops were designed, and the total number of bumps per chip was 544. The resistance change of the outermost loop was monitored during the temperature cycling test and mechanical drop test. The other bumps on the seven inner loops could provide enough mechanical support, such that the package did not easily fail. The detailed design of the silicon chip and BT substrate is given in Table I. 200 μm was determined as the pitch size because it is a common pitch value of conventional Cu pillar. Silicon chips with standard thickness of 525 μm were fabricated by Al sputtering and patterning, followed by silicon dioxide deposition and etching. BT substrates with thickness of 600 μm were fabricated by 12 μm thick Cu laminating, followed by Cu etching and organic solderability preservative (OSP) depositing to prevent oxidation of the Cu. Fabricated silicon chip and BT substrate are shown in Fig. 1 (a) and (b), respectively.

III. FABRICATION AND CHARACTERIZATION OF THE JOINTS MADE OF CU PILLAR MICRO-BUMPS WITH PRINTED POLYMER CORES

A. Surface Metallization

Micro-scale and cylindrical polymer cores with diameter of 20 μm and height of 30 μm were fabricated by aerosol jet printing with synchronized in situ UV LED curing, as shown in Fig. 2. The process of surface metallization started with seed layer sputtering and there was a concern about the adhesion between Cu and polymer core due to the difference in stiffness and other properties [21]. Thus, a buffer layer was required between Cu and polymer core. In fact, TiW was a common buffer layer which provided strong adhesion on both polymer core and Cu. In this study, 0.1 μm TiW was sputtered, followed by 0.5 μm Cu seed layer sputtering. Since the sputtering temperature cannot go beyond the melting temperature of polymer core, a low power (600W) sputter equipment (Denton Explorer, Denton Vacuum, Moorestown, NJ, USA) was utilized. The sputtering process was divided into several sessions and enough cooling time was applied among each sputtering session, such that the substrate temperature could be kept at room temperature. And the polymer core material (UV curable acrylic resin) has been demonstrated to withstand short-term high temperature shock, such that strong adhesion could be maintained in the subsequent processes. After seed layer sputtering, Cu/Sn electroplating mold was formed by photoresist coating and patterning. 5 μm Cu and 2 μm Sn was coated to fulfill the target. After photoresist and seed layer removal, the Cu pillar micro-bumps with printed polymer cores with diameter of 35 μm and height of 35 μm were achieved. The process flow to fabricate the Cu pillar micro-bumps with printed polymer cores is provided in Fig. 3 (a) and these fabricated micro-bumps are shown in Fig. 3 (b). The cross-
section of a typical Cu pillar micro-bump with printed polymer core is given in Fig. 4. No defect was observed at the sputtering interface and the dimension was almost the same with the design value. Conventional Cu pillars were fabricated by Cu/Sn electroplating. In order to maintain the same dimension and Cu/Sn volume ratio of the conventional Cu pillars as the Cu pillar micro-bumps with printed polymer cores, 25 μm Cu and 10 μm Sn was electroplated. The process flow to fabricate the conventional Cu pillars is provided in Fig. 5 (a) and the fabricated conventional Cu pillars are shown in Fig. 5 (b).

B. Flip-chip Bonding

Reflow bonding of silicon chips with BT substrates was performed to form the joints made of Cu pillar micro-bumps with printed polymer cores. To compare, conventional Cu pillars were bonded with BT substrates using the same reflow profile. Fig. 6 (a) provides the reflow profile. Metal oxides were removed by flux. In order to make sure every bump at the chip side fully touched the Cu pads, 25 mN compression force per bump was applied to the silicon chip at 260℃ for 30s. In order to prevent oxidation during the reflow process, N₂ gas was
applied during the entire reflow period. This bonding profile was compatible with conventional Cu pillar bonding process. Fig. 6 (b) shows a typical sample after bonding.

C. Cross-Section Observation

Bonding interface was an important factor to evaluate the bonding quality. Cross-sections of the joints of the conventional Cu pillar and the Cu pillar micro-bump with printed polymer core are shown in Fig. 7 (a) and (b). The diameter and the height of both joints were designed to be equal so that a fair comparison could be achieved. It was observed that both joints were well formed without any defect or cracking. The IMC (intermetallic compound) was clearly identified at the bonding interface of the joint of the Cu pillar micro-bump with printed polymer core (see Fig. 8).

D. Joint Resistance Measurement

Joint resistance was an important parameter to assess the joint performance. The joint resistance measurement by the Kevin method was conducted. Sufficient samples were prepared to ensure the measurement quality. The measurement setup is shown in Fig. 9 (a) and the measured daisy chain loop is shown in Fig. 9 (b). Since the resistance of the Cu trace and Al trace was very small compared with the joint resistance, the
trace resistance could be ignored. Therefore, the resistance per joint could be achieved based on the measured daisy chain loop resistance and the results are provided in Fig. 10 (a). The resistance per joint of the Cu pillar micro-bumps with printed polymer cores was twice of that of the conventional Cu pillars. The reason was that the conducting area of the joint with the polymer core was less because polymer core was not conductive, as illustrated in Fig. 10 (b).

IV. RELIABILITY TESTS

A. Temperature Cycling Test

Sufficient sampling was done on the specimens for both temperature cycling and mechanical drop tests to ensure the quality of experiments. 16 samples with joints of conventional Cu pillars and 14 samples with joints of Cu pillar micro-bumps with printed polymer cores were prepared for the temperature cycling test. According to the standard of IPC-9701 [22], the failure criterion was set at 1000Ω. The initial resistance of the daisy chains for conventional Cu pillars was ~15Ω and that for Cu pillar micro-bumps with printed polymer cores was ~25Ω. The picture of a typical sample is given in Fig. 11 (a). Service condition J (0°C-100°C) was adopted for temperature cycling based on JESD22-A104D [23]. The reason for choosing condition J was that the glass transition temperature (Tg) of the polymer core material was around 100°C. The temperature cycling test profile is given in Fig. 11 (b) and the Weibull plot of the temperature cycling test is given in Fig. 12. It was concluded that Cu pillar micro-bumps with printed polymer cores may improve the characteristic life by 32%, compared with conventional Cu pillars. Failure analysis by dye penetration was conducted. It was confirmed that, in both cases, solder joints were failed at the corner of BT substrate side IMC region (see Fig. 13).

B. Mechanical Drop Test

8 samples with joints of conventional Cu pillars and 8 samples with joints of Cu pillar micro-bumps with printed polymer cores were prepared for the mechanical drop test. According to JESD22-B111A [24], the failure criterion was set at 100Ω. The initial resistance of the daisy chains for conventional Cu pillars was ~15Ω and that for Cu pillar micro-bumps with printed polymer cores was ~25Ω. The picture of a typical sample is given in Fig. 14 (a). Service condition A (500G peak acceleration and 1 ms pulse duration) was adopted for mechanical drops based on JESD22-B104B [25]. The testing condition is given in Fig. 14 (b) and the Weibull plot of the mechanical drop test is shown in Fig. 15. It was concluded that Cu pillar micro-bumps with printed polymer cores may improve the characteristic life by 411%, compared with conventional Cu pillars. Failure analysis by dye penetration was
conducted. There existed two distinct failure modes, one at the BT substrate side and the other at the silicon chip side. It was confirmed that, in both cases, failure mode at the BT substrate side was the IMC failure shown in Fig. 16. Fig. 17 shows that the failure mode at the silicon chip side was the under bump metal (TiW/Cu) interface failure. Further failure analysis will

Fig. 13. Post temperature cycling SEM and EDS inspection with (a) with conventional Cu pillars and (b) with Cu pillar micro-bumps with printed polymer cores.

Fig. 14. (a) Sample appearance and (b) mechanical drop test condition.

Fig. 15. Weibull distribution of failure data under mechanical drop test.

Fig. 16. Post mechanical drop SEM and EDS inspection with (a) with conventional Cu pillars and (b) with Cu pillar micro-bumps with printed polymer cores.
have to be performed in order to understand the root causes of various failure modes. Nevertheless, this distinction in failure modes should not affect the conclusion of the Weibull analysis.

![Image](https://via.placeholder.com/150)

Fig. 17. Post mechanical drop SEM inspection: with (a) conventional Cu pillars and (b) with Cu pillar micro-bumps with printed polymer cores.

V. CONCLUSION

Cu pillar micro-bumps with printed polymer cores with diameter of 35 μm and height of 35 μm were achieved by surface metalization. For comparison, conventional Cu pillars of the same diameter and height were fabricated. The joints were achieved by flip-chip bonding of the silicon chip with the BT substrate. There were no cracks or voids observed at the bonding interface for both joints and IMC was clearly identified by EDS. The resistance of the Cu pillar micro-bump with printed polymer core joints was twice of that of the joints made of conventional Cu pillar because the polymer core was not conductive. The reliability of the joints made of the Cu pill micro-bumps with printed polymer cores and joints made of conventional Cu pillars were investigated under temperature cycling and mechanical drop tests. With the extra compliance provided by the printed polymer cores, the characteristic life in temperature cycling and in mechanical drop increased by 32% and 411%, respectively. It was verified that the structure of Cu pillar micro-bumps with printed polymer cores can effectively improve the joint reliability.

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