Wetting characterization of Flip chip’s Lead-Free Solder Interconnect Using Surface Evolver.

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Abstract. Smaller pitch of first interconnect has posed various challenges to the electronic packaging. The driver to smaller pitch was driven by package and die size miniaturization. In order to enable smaller pitch of first interconnection, copper pillar was introduced. In this paper, surface evolver software was used to predict the solder geometry of solder cap copper pillar onto copper pad process. The study has shown that copper pillar solder joint geometry can be successfully simulated and agreed with experiment. The relationship between various solder joint influencing factors such as die bump diameters, copper pad geometry, solder height and solder volume were established. The optimum die to copper pad width ratio can be obtained through this simulation work. The information can be used to estimate critical volume of solder needed for new, smaller pitch die bump and copper pad design which help to save money and time by avoiding a large number of experiments prior to mass production.

1. Introduction

1st interconnect between die bump and substrate bump in flip chip packages has evolved from solder bump- pre-solder bump substrate joint to copper pillar- pre-solder bump substrate and further evolved into solder cap copper pillar on copper trace. Small die size requirements as a result of transistor size reductions have driven the need to adopt finer die interconnect pitches. Copper pillar with solder cap is able to provide interconnect with smaller solder joint diameter. The adoption of copper pillar was mainly for smaller bump pitch especially below 150 micron. Copper pillar has shown improvement in electro-migration performance over SnAg and SnPb bump for the same current/temperature condition and similar bump/UBM geometry [1-2]. Additionally, copper pillar has superior characteristic which allow high density input/output (> 200 IO) and current capacity afforded by copper pillar bumping. It is easier to control the pillar bump diameter and stand-off height, which are critical for fine-pitch packages.

Solder cap copper pillar on copper trace provided desirable advantage over other solder joint interconnects as it enables finer pitch interconnect joining for miniature device with minimum solder bridging yield losses. Under solder cap copper pillar process, a solder cap copper pillar directly bond onto copper trace and formed a interconnect joint under thermal compression bonding reflow. The surface of the pads on the substrate is Cu-OSP (Organic Solder ability Preservative) and a pre-solder is not required. Thermal compression bonding was used as it is able to control solder reflow spread and the standoff height versus mass reflow. Solder die bump- pre-solder bump substrate joint have been
reported to result in defects during manufacturing process such as solder bridging when die bump pitch goes below 140 micron [3]. In this study, the open source Surface Evolver software will be used to simulate the solder joint wetting characteristic under different solder height position, solder volume and different copper pad width. The solder wetting characteristic such as contact angle, stand-off height and its solder surface angular values were measured. The simulation result able to model the solder shape seen in manufacturing process.

2. Experimental study

Solder shape geometry was predicted for solder cap copper pillar direct bonding on the copper pad using surface evolver [4]. Surface Evolver is a computer program that able to predict the solder shape formation. The shape will evolve through minimizing the energy of an initial surface subject to constraints that the user defined. Different pad geometry, solder volume, and solder height were part of the factors used in this simulation work. The solder joint height in this simulation was user defined, varied from 8 micron to 45 micron to simulate the solder joint height formation which is controlled by thermo-compression process. The simulation work in this study was compared with published solder joint geometry in experiment [5] to validate the model. In this simulation, copper pillar height 55 micron with diameter 7 micron with different solder cap height was bonded onto rectangle shape copper pad 125 micron length x 85 micron pad width. As this is bump on trace process, the length was constraint at 125 micron which was longer than is needed to cause any impact to the solder shape. Only copper pad width will have influence to the shape formation. From the model established, various solder volume, joint height and pad width were simulated to predict the solder shape. Copper pillar geometry was fixed as it does not reflow under the lead free reflow profile peak at 260 °C. Solder cap was melted and spread on the copper pad. The spread of the solder depends on the wetting angle between solder and copper pad, volume and pad geometry.

Solder shape geometry in the experiment includes solder fillet, solder spread and wetting angle. Solder shape from simulation was characterized in a similar way and compared to the published solder shape geometry in the experiment.

\[ R_r = \text{Right solder joint fillet radius} \]
\[ R_l = \text{Left solder joint fillet radius} \]
\[ S_r = \text{Right solder spread from the die bump edge} \]
\[ S_l = \text{Left solder spread from the die bump edge} \]
\[ \theta_r = \text{Right wetting angle} \]
\[ \theta_l = \text{Left wetting angle} \]

![Figure 1. Schematics of solder shape geometry characterization.](image)
Table 1. Solder joint geometry with variable solder cap volume and copper pad width

| Copper pillar diameter (micron) | Copper pillar height (micron) | Substrate Pad with height (micron) | Solder height (micron) | Die bump offset (micron) | Solder cap volume (Kilo-micron^3) | Copper pad width (micron) |
|---------------------------------|-------------------------------|-----------------------------------|------------------------|--------------------------|-----------------------------------|--------------------------|
| 70                              | 55                            | 85                                | 8                      | 0                        | 89.8, 56.3, 30.8                  | 45, 55, 65, 75, 85       |

3. Results and discussion

Figure 2 was obtained from the simulation with solder height controlled to 8 micron, solder volume 89.8 kilo-micron^3 on copper length 125 micron and 85 micron pad width. The solder joint shape geometry was characterized with solder spread on the copper pad (S). The solder shape geometry characterization result was recorded in Table 2. Figure 2 shows the slight concave shape which are resulted from large contact area of solder on copper pad 125 micron length where the solder able to spread. From the side view, Figure 3 is for the pad with 85 micron pad width, and solder spread is constraint by solder resist near to the pad. From the result, the simulation data collected was found to agree with solder shape geometry from the experiment. Solder spread and solder fillet were well correlated as shown in Table 2.

![Figure 2. Solder joint shape of 125 length x 85 micron width with 70 micron copper pillar diameter- front view](image1)

![Figure 3. Solder joint shape of 125 micron length x 85 micron width with 70 micron copper pillar diameter-side view](image2)

Table 2. Comparison solder joint shape geometry between simulation and experiment.

| Sample            | Right Angle (Degree) | Left Angle (Degree) | Right Radius Solder Fillet (micron) | Left Radius Solder Fillet (micron) | Right Spread (micron) | Left Spread (micron) |
|-------------------|----------------------|---------------------|-------------------------------------|-----------------------------------|-----------------------|----------------------|
| Experiment Data   | 40                   | 40                  | 38.5                                | 38                                | 18.3                  | 18                   |
| Simulation data   | 40                   | 40                  | 38.8                                | 38.8                              | 18                    | 18                   |
Different solder joint height effect to solder shape geometry was shown in Figure 4. It can be observed that the solder joint height shall be < 15 micron before hourglass shape started to appear for a given solder volume. The hour glass shape has reduced the solder joint strength mechanically under temperature cycle for copper pillar-solder joint [6] as the crack initiation started at the necking area of tin solder. Since right and left side shape is symmetry, the left side of the solder shape characteristic was plotted against solder height as shown in Figure 5. Solder spread is getting smaller when the solder joint height was increased. While solder radius is on decreasing trend until solder joint at 45 micron, the radius started to increase with smaller solder spread and slimmer solder joint shape like “necking”. The relationship is important for package engineer to determine the optimized solder volume for a given die bump/pad width ratio.

| Solder Height (micron) |
|------------------------|
| 8          | 15          | 25          | 35          | 45          |

**Figure 4.** Solder shape geometry at different solder joint height at constant solder volume.

![Solder shape geometry at different solder joint height at constant solder volume.](image)

**Figure 5.** Solder spread and fillet radius at different solder joint height with constant solder volume.

![Solder spread and fillet radius at different solder joint height with constant solder volume.](image)

Figure 6 shows the effect of die bump/copper pad width ratio and different solder volume towards solder joint geometry. When the die bump/copper pad width ratio increased, the solder shape changed from inwards solder fillet to outwards fillet like barrel shape. When the volume of solder decreased, necking started to appear. Critical volume for a cylindrical shape from the calculation was 3.08x10³ mm³ for 8 micron solder joint height and 0.8 ratio of die bump to copper pad width. However, there is still minor necking on the shape as it is due to surface tension effect on copper pad where some of solder volume was spread out. From the modelling, critical volume was found at 3.10x10³ mm³ about 0.65% delta. It has shown that the model established was accurate.
It was reported that 35 micron solder cap (8.98x10^{-5} mm^3) and 85 micron pad width showed better stability from 1100h High Temperature Storage (HTS) test experiment at 175 °C compared to 25 micron (5.63x10^{-5} mm^3) [5]. This was due to larger solder thickness to allow better creep and thermomechanical stress. The experimental data [5] has shown that smaller die bump to copper pad width ratio with solder cap 35 micron is preferred. To cater for smaller pitch of first-level interconnect, reducing copper pillar diameter to UBM ratio is preferred as it helps to reduce the stress on low-k electric layer. As a result, smaller space between 2 adjacent solder joints. It is preferred to have smaller die bump to copper pad width ratio from assembly process perspective since higher die bump to copper pad width ratio has increased the chances of solder bridging between 2 adjacent solder joint interconnect. It was due to the solder geometry that tends to be barrel shape when die bump to copper pad width increased which create an easier path for solder bridging to adjacent trace or bump. Surface evolver can be used to estimate the bump shape given a known die bump to copper pad width ratio and solder volume which will help to decide the critical distance required for trace to trace spacing.

4. Conclusion

From the simulation work, the solder joint shape of the copper pillar solder cap onto copper pad was successfully predicted and agreed to publish experimental data. The validated model was extrapolated to predict the relationship of die bump/pad width ratio with different solder volume. Higher solder volume is required for lower die bump/pad width ratio. It is found that critical volume from this simulation work was 0.65% delta from the calculation and extrapolation model is deemed reliable.
References

[1] Yeoh A, Chang M, Pelto C, Huang TL, Balakrishnan S, Leatherman G 2006 Electronic Components and Technology Conference 1613
[2] Syed A, Dhandapani K, Nicolls L, Moody R, Berry CJ and Darveaux R 2010 IMAPS Device Packaging Conference 169
[3] Gerber M, Beddingfield C, and O’Connor S 2011 Electronic Components and Technology Conference 612
[4] Brakke K A 2013 Surface Evolver Manual Version 2.70
[5] Ebersberger B, Lee C 2008 Electronic Components and Technology Conference 62
[6] Huang YW, Zhan CJ and etc 2014 Electronic Components and Technology Conference 1911
[7] Wang YW, Lu KH, Jay Im and Ho Paul S 2010 Electronic Components and Technology Conference
[8] Eslampour H, Joshi M, Kang KT, Bae H, Kim YC 2012 IEEE 905