A NOVEL SOLDER PUMP STRUCTURE AND ITS POTENTIAL APPLICATION IN THROUGH WAFER INTERCONNECTION (TWI) FOR MEMS PACKAGING

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Abstract — *Through wafer interconnection (TWI) is a critical technology for 3D MEMS packaging. In this report a novel 'solder-pump'-based TWI is proposed. It employs the surface tension force of the molten solder to pump solder to through wafer holes and therefore to form an interconnection. 3D simulations and theoretical analysis of this are presented, along with experimental results obtained via solder reflow. Compared with conventional TWI, this solder-pump technique is simpler in process, lower in resistance and more compatible with surface mounting technology.*

Key Words: *through wafer interconnection (TWI), solder reflow, wafer-level- packaging (WLP)*

I INTRODUCTION

Through wafer interconnection (TWI) is a critical and enabling technology for 3D wafer level packaging for MEMS. Furthermore, compared to conventional planar feed-through technologies, TWI offers several advantages such as higher connection density, lower resistance and smaller parasitics in RF circuits.

Currently two main TWI techniques have been developed. The first TWI technique was proposed by Hyongsok T. Soh and his colleagues at Stanford University in 1998, and is named through wafer via (TWV). The main process involves through wafer etch, CVD metallization and electroplating, followed by patterning and etching [1][2][3].

The second TWI is named Silex Via, which was developed by Silex Microsystems Ltd. The technique behind Silex Via is the use of low resistivity through-wafer silicon pillars formed by DRIE to serve as a conductive medium. The trenches between the pillars and the main wafer body are then filled with dielectric materials for electrical isolation [4].

Both of these two techniques have disadvantages. For TWV, the involved CVD metallization and electroplating has a geometric constraint problem. Deposition of metal on the sidewall of the through wafer hole with a high aspect ratio is always a challenge. For Silex Via, using silicon as a conductive medium produces a relative larger resistance than metals. Furthermore, to make both the TWV and the Silex Via surface mounting compatible, additional solder balls needed to be attached on the interconnection ends.

In this report, a novel solder-pump based TWI technique is proposed. The principle of this technique is employing the surface tension force of the molten solder to pump solder to through wafer holes to form TWI. This technique promises several advantages over current methods for TWI: It has smaller electrical impedance; avoids the geometrical constraint of metal deposition; and is more compatible with surface mounting technology (SMT).

II STRUCTURE AND MECHANISM

II.1 CONFIGURATION OF THE STRUCTURE

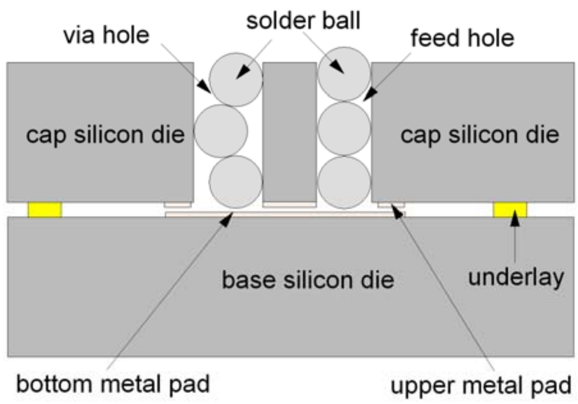


Figure 1. Cross-section schematic of the solder-pump structure with solder balls placed in the holes.

Figure 1 illustrates the cross-section schematic of the solder-pump structure, which is configured by a cap silicon die and a base silicon die. The cap silicon die is fabricated with through wafer holes with different diameters. The key in this structure is that the diameter of the via hole is slightly bigger than that of the feed hole. The gap formed by both the metal pads and the underlay creates a flowing channel for the molten solder.

II.2 MECHANISM OF THE SOLDER PUMP

The reflow of the solder balls in the solder pump can be divided into two steps: the first step is spreading and combination. After the temperature reaches the melting point, solder spreads along the metal pads and combines in the channel between the metal pads. The second step is pumping the solder from the feed hole to the via hole. Because both silicon and silicon dioxide are non-wettable materials to solder, at the end of the first reflow step, semi-spherical surfaces are formed both in the via hole and the feed hole.

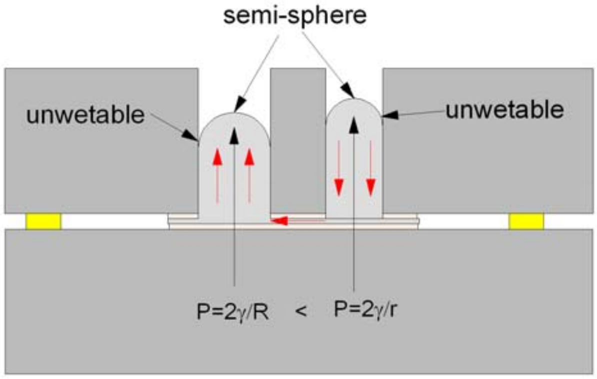


Figure 2. The mechanism of the solder pump.

By the force balance condition, the pressure generated with a spherical cap can be derived by

$$P = \frac{2\gamma}{r}$$

Where γ is the surface tension of molten solder, and r is the radius of the sphere. Because the radius of the feed hole is smaller than that of the via hole, the pressure generated in the feed hole is therefore bigger than that in the via hole. The pressure difference drives the solder from the feed hole to the via hole, as shown in Figure 2. This transfer stops when the solder in the feed holes form spherical caps, whose pressure equals the pressure in the solder bump capping the via hole. Finally, the solder in the via hole achieves TWI. Table 1 lists some examples of the pressure within through wafer holes that have different radii.

Table 1. Pressure within through wafer holes for 300 μm solder balls (0.55 N/m is used as surface tension here).

r	165μm	155μm	Δr = 10 μm
P	6667 Pa	7097 Pa	ΔP = 430 Pa

III SIMULATION AND ISSUES

III.1 3D SIMULATION

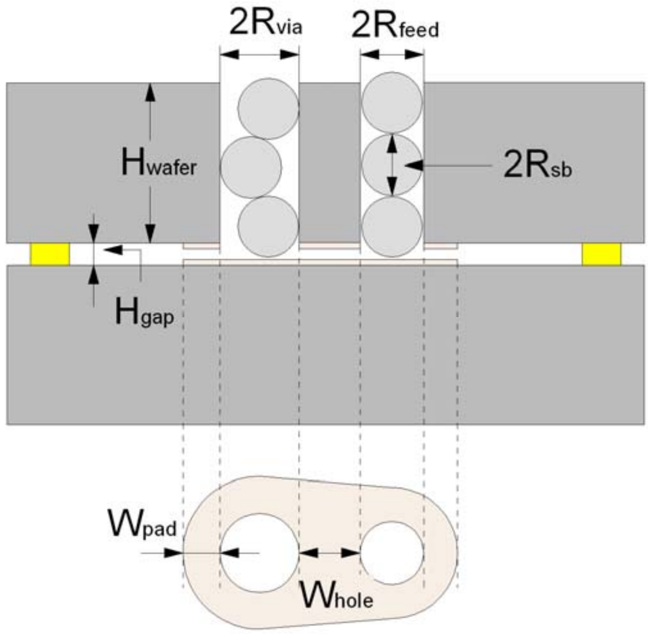


Figure 3. Parameters of the solder pump.

Figure 3 shows the geometric parameters of the solder pump structure. The pumping step of the reflow is simulated in Surface Evolver to obtain the final shape of the solder.

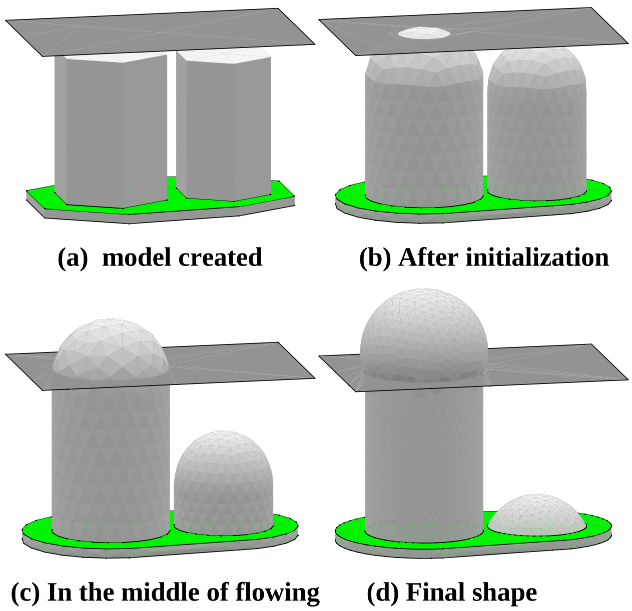


Figure 4. Surface Evolver simulated the shape of the solder in the solder pump. The grey quadrangle indicates the surface of the wafer.

As we can see from Figure 4, the solder flows from the feed hole to the via hole and finally forms the shape shown in Figure 4 (d). The final shape of the solder includes four parts: a bump in the feed hole;

a plate between metal pads; a cylinder inside the via hole which serves as the conductive medium for TWI; and a solder bump capping on the via hole. There is a possibility that the solder bump capping on the via hole is ready for surface mounting.

III.2 ISSUES

The first issue is the optimization of the stand-off height (H_{gap}). On one hand, the solder consumed in the space between two metal pads should be minimized. On the other hand, the stand-off height also affects the flow rate of the molten solder. The bigger the channel between the metal pads, the easier for solder reflow. It is estimated that the stand-off height is between 10 µm - 50 µm.

The second issue is volume constraint. In this solder pump, the solder used is in the form of a ball, and the total volume of the solder is therefore integrals of the volume of single solder ball. Through calculation, it is found that depending on the diameter of the via hole, multiple feed holes may be needed to provide sufficient solder quantity. Assuming that the space between the metal pads and the solder bump capping on the via hole consume one solder ball respectively, the number of feed holes needed can be roughly calculated using the following formula:

$$N_{feed} = \frac{3R_{via}^2}{2r_{sb}^2} + \frac{4r_{sb}}{H_{wafer}}$$

where R_{via} and r_{sb} are the radii of the via hole and solder ball respectively, and H_{wafer} is the thickness of the wafer.

The third issue is the lifting of the cap die. During the reflow, the surface tension and the pressure within the molten solder yield a lifting force on the upper metal pad. This lifting force can result in the failing formation of the solder pump (shown in Figure 5) by lifting the cap, and thus a sufficient load weight is needed.

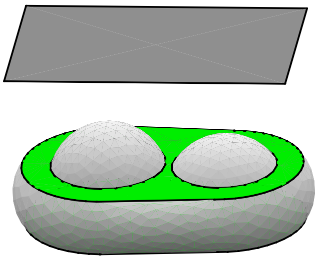


Figure 5. Surface evolver simulated failure of forming a solder pump because of the inefficient load weight.

To theoretically analyze the lifting force, the bond number B_o is calculated to determine whether the effect of gravity should be considered [x].

$$B_o = \frac{\gamma}{\rho g L^2}$$

Here γ and ρ are the surface tension and density of the molten solder respectively. L is the characteristic length scale of the solder pump structure. In terms of the parameter values listed in Table 1, $B_o \approx 30$. Thus, the gravity effect is negligible.

Table 2. Parameter values of the solder balls.

Parameter	Density	Diameter	Surface tension
Unit	kg·m3	mm	N/m
Value	7.26×10^3	0.3/0.1	0.55

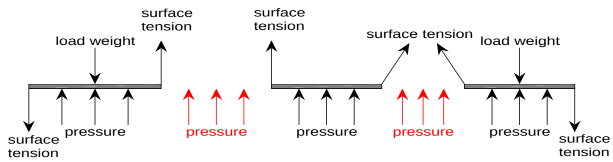


Figure 6. Forces acting on the upper metal pad.

Figure 6 illustrates the forces acting on the upper metal pad. In terms of the force balance condition, it can be shown that the minimum load weight to prevent the lifting of the cap die is:

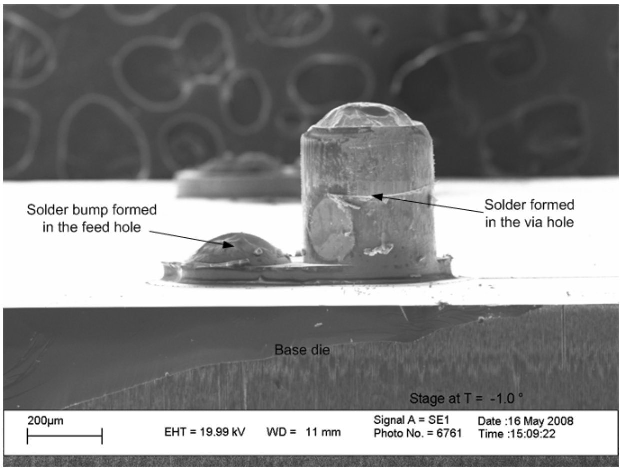
$$W_{load} = \gamma\left(\frac{2S_{pad}}{R_{feed}} - L_{pad}\right)$$

where W_{load} is the load weight, and S_{pad} and L_{pad} are the area and perimeter of the lower metal pad, respectively. By the equation above, the lifting force for the model in Figure 4 is about 1.5mN, while it is 1.4mN calculated in Surface Evolver.

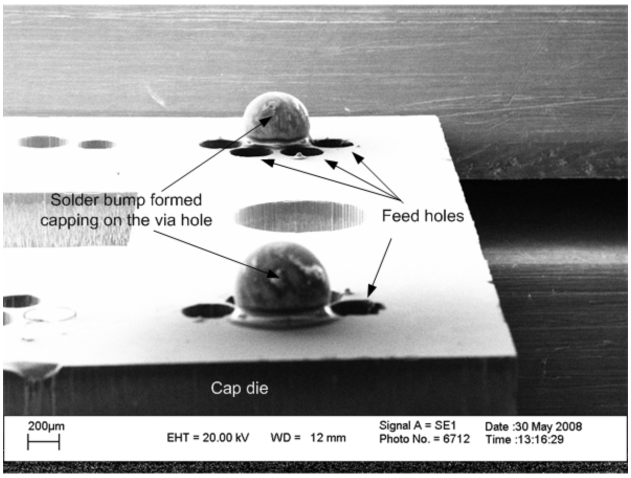
IV RESULTS AND CONCLUSIONS

IV.1 RESULTS

Solder balls of 300 µm diameter were used in the reflow experiment. The diameter of the via hole is 25% bigger than that of the solder balls, compared to that of the feed hole, which is only about 4% bigger. Both the feed hole and via hole were loaded with two solder balls. The initial stand-off height between the two dies was about 50 µm. The maximum reflow temperature reached was nearly 250 ºC, while the melting point of the solder ball is about 220 ºC. Figure 8 shows the SEM images of the solder formed inside the solder pump where the cap die has been removed. It can be seen that the shape of the solder is very similar to the simulated result in Figure 4(d). The insuffient of the solder is solved by using multiple feed holes. Figure 8(b) shows the solder bump formed capping on the via hole when multiple feed hole structure is used. Since both silicon and silicon dioxide are unwetable materials, it is expected that when the isolation is achieved by oxidation of the sidewalls of the through wafer holes, the same solder behavior should be observed.



(a)



(b)

Figure 8. SEM images of the solder pump after reflowing. (a) solder inside the cap die (with the cap die being removed) (b) bump formed capping on the via holes.

IV.2 CONCLUSION

A novel solder pump structure is proposed and its potential application in solder based TWI is demonstrated. Also, the issues related to the solder pump have been discussed. There are several advantages of the solder pump based TWI over currently TWI technologies: (a) Lower resistance: due to the high electrical conductivity of the solder and the large cross-sectional area of the through wafer hole, the electrical impedance can be on the scale of mΩ; (b) Simpler processing: compared with TWV, the geometric constraint of depositing metal in high-aspect ratio through wafer holes is avoided, because no metal deposition is needed; (c) More compatible with surface mounting technology (SMT): the solder bump capping on the via hole is ready for surface mounting, while in current TWIs, additional solder balls are needed to make them SMT compatible; (d) Offering the possibility to achieve bonding and interconnection in one reflow run, when solder is chosen as bonding material.

Further work includes decreasing the diameter of the interconnection by using solder balls of 100 µm diameter, and obtaining isolation by oxidation of the sidewall of the through wafer holes before reflow.

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