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Solder Pump Technology for Through-Silicon via Fabrication

Jiebin Gu, W. T. Pike, and W. J. Karl

Abstract—**We present a solder pump method that injects conductive material into a device wafer to form low-resistance through-silicon vias (TSVs). Building on previous work that exploits the Gibbs–Thomson effect, this pump geometry uses a reusable wafer set to produce a pattern of U-shaped reservoirs into which solder balls are loaded. After introduction of the device wafer with a corresponding pattern of through-wafer-etched holes, reflow results in the complete transfer of the solder from the reservoirs into the device structure to produce the vias. This approach forms the basis of a rapid low-cost batch-fabrication process for TSVs. [2010-0335]**

Index Terms—**Microelectromechanical devices, semiconductor device packaging, through-silicon via (TSV).**

I. INTRODUCTION

The demand for low-cost through-silicon via (TSV) technologies is growing for device packaging applications, such as wafer-level and 3-D integration [1]. Current methods to form such interconnects involve the use of electroplating [2] or require unconventional materials and processes [3]–[5].

We have demonstrated the use of the Gibbs–Thomson effect in a simple solder pump to create metal vias [6]–[8]. Surface tension is used to pump molten solder into a through-wafer-etched via hole, forming an electrically conductive path. The solder itself is introduced in the form of solder balls, a material which has found widespread use in device packaging.

In this letter, an advanced solder pump structure which overcomes our previous requirement to load solder balls through the device wafer, and hence is fully compatible with practical batch fabrication, is proposed, modeled, and demonstrated.

II. SOLDER PUMP DESIGN

Solder reflow has been used extensively for self-assembly of microelectromechanical systems structures [9]. There are two fundamental conditions that need to be fulfilled for any reflow-based solder pump to work: 1) The solder, whether in the form of balls or other geometries, should be able to coalesce into a continuous volume after melting; this can be assisted by solder-wettable metal pads or achieved by direct solder contact, and 2) a pressure differential induced by surface tension should be maintained during the entire reflow to ensure flow of solder into the final geometry.

To fulfill these conditions, the current solder pump is formed in three parts (Fig. 1): 1) a reservoir, which contains the solder material prior to reflow; 2) a device die, through which the via of radius $r_{\rm via}$ is formed; and 3) a spacer, which provides separation between the device die and the reservoir. The reservoir is formed by two silicon dies, namely, a feed die with a pair of feed holes of different radii $r_{\rm feed1}$ and $r_{\rm feed2}$ and an underpass die which provides a connection between the two feed holes and therefore links the volumes into a single reservoir, as shown in Fig. 2(a). For surface tension to drive the liquid solder into the via, the geometry has to fulfill the following inequalities:

$$r_{\rm feed1} < r_{\rm feed2} < r_{\rm via}. \tag{1}$$

The differential radii $r_{\rm feed2} - r_{\rm feed1}$ and $r_{\rm via} - r_{\rm feed2}$ are critical parameters for a solder pump design and have to fulfill competing requirements: They should be large enough to set sufficient pressure differentials to both overcome the static and dynamic resisting forces, such as gravity and sidewall drag, and drive the liquid solder into the via hole sufficiently fast; sidewall roughness due to the fabrication process will increase the dynamic resistance and hence slow the reflow process which should be completed within seconds to avoid any solder–alloy segregation. However, too large a differential radius decreases the achievable via aspect ratio given a fixed solder-supply volume.

Assuming ideal conditions, with perfectly smooth parallel sidewalls, gravity is the only force that needs to be overcome. Assuming a single value for the differential radius $\Delta r = r_{\rm feed2} - r_{\rm feed1} = r_{\rm via} - r_{\rm feed2}$ and $\Delta r \ll r_{\rm ball}$, the condition that surface-energy forces can overcome gravity can be expressed as

$$\Delta r > 2N r_{\rm ball}/(3B_o) \tag{2}$$

where N is the total number of individual solder balls and B_o is the dimensionless Bond number ($B_o = \gamma/\rho g r_{\rm ball}^2$) which gives the relative strength of these two forces. For 300-μm solder balls of a typical lead-free composition corresponding to $B_o \approx 85$, if six solder balls are required to form the via, (2) gives a differential radius Δr of 7 μm. In our design, Δr is chosen with some margin to ensure a sufficient pressure differential to overcome additional drag forces due to the sidewall roughness and hence fulfill the requirement of a rapid reflow completion.

A further critical stage for a successful reflow is the movement of the solder volume through the underpass [Fig. 3(e)]. Here, the following two additional conditions have to be satisfied: 1) The head of the solder volume has to flow out of the second feed hole before the tail leaves the underpass, hence ensuring that the solder will not be trapped in the second feed hole, and 2) the internal solder pressure generated in the underpass, which is controlled by the thickness h and width w, shown in Fig. 2(b), should be greater than the back pressure from the solder in the second feed hole.

The aspect ratio AR of the via is defined by $AR = t_{\rm device}/2r_{\rm via}$, where $t_{\rm device}$ is the thickness of the device wafer. Assuming that the final solder geometry is a cylinder with hemispherical caps and $\Delta r \ll r_{\rm ball}$, the aspect ratio is given by

$$AR \approx \frac{2}{3}(N-1). \tag{3}$$

This approximation implies that the aspect ratio is proportional to N, which, in turn, depends on the thickness of the feed die and the size of the solder ball. For a fixed thickness of the feed die, the smaller the solder ball used, the more the solder balls can be placed in the reservoir structure. The smallest solder ball commercially available is

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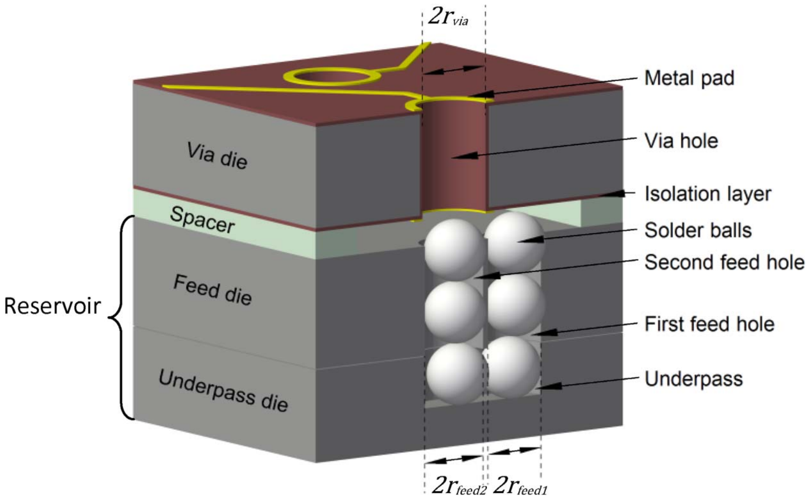


Fig. 1. Cross-sectional schematic of the advanced solder pump structure.

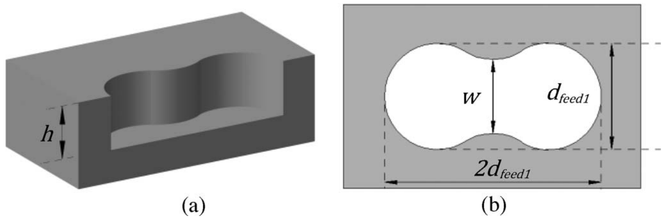


Fig. 2. (a) Three-dimensional illustration of the cross section of the underpass. (b) Contour geometry of the underpass.

100 μm, which gives, for a 525-μm-thick feed die, an aspect ratio of up to seven.

Fig. 3 shows the assembly and reflow mechanism of the solder pump. The inequalities in (1) ensure a driving force as the reservoir is emptied [Fig. 3(d) and (f)] [6].

III. EXPERIMENTAL PROCEDURE

The reservoir consisting of the feed die and the underpass die was fabricated from standard 100-mm 525-μm-thick double-side-polished silicon wafers by deep-reactive-ion etching (DRIE). The device dies were fabricated from a 300-μm-thick double-side-polished silicon wafer, with the fabrication process split into the following three main steps: 1) DRIE of the through-wafer holes into the silicon substrate; 2) dry oxidation to form an electrical isolation layer; and 3) multilayer thin-film metal deposition through a shadow mask to produce solder-wettable areas. The actual assembly and reflow process are described in detail in [6].

IV. RESULTS

Initial results confirmed that a sufficient differential radius and a fast heating profile were required for reliable reflow. The pressure differential defined by the reservoir geometry can be negated by a compositional variation in surface tension due to segregation, preventing successful completion of the reflow. As the surface tension γ is a function of solder composition, reflow temperature, and oxygen concentration in the reflow environment [10], [11], fast reflow under repeatable conditions is required. The following geometry was successful: a first feed hole of 312 μm in diameter (allowing a solder ball tolerance of 10 μm and with an additional margin for the sidewall roughness), a second feed hole of 362 μm in diameter ($\Delta r = 25$ μm), a via hole of 412 μm in diameter, and an underpass of 295 μm in depth (h) and of a minimum width (w) of 260 μm.

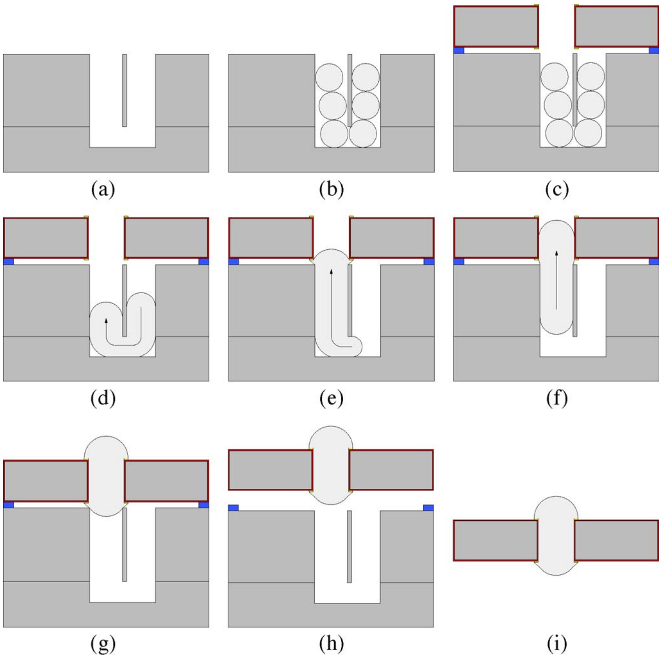
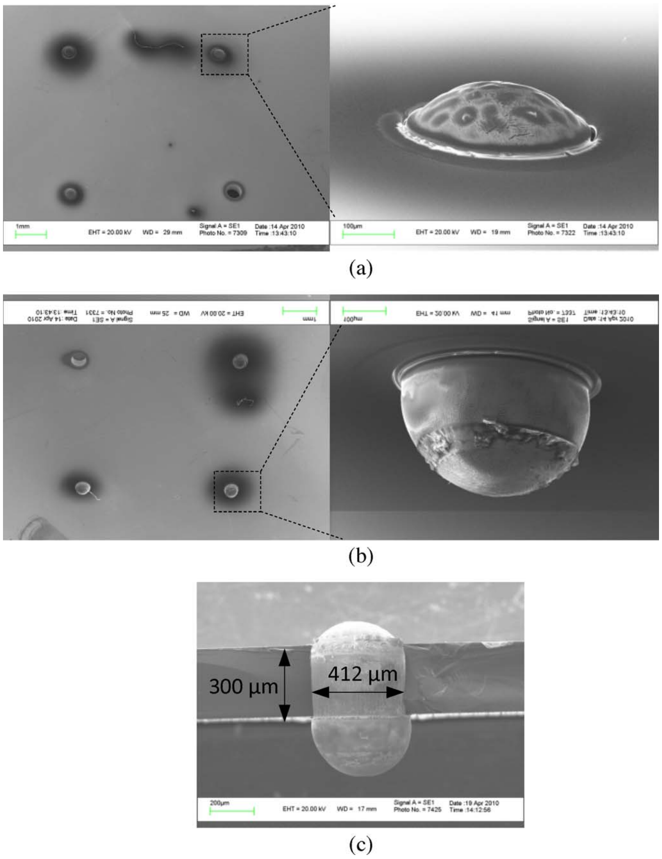


Fig. 3. Solder pump procedure for TSV fabrication. (a) Assembly of the reservoir structure. (b) Solder ball loading. (c) Mounting of the device die. (d)–(g) Driven by surface tension, the liquid solder travels along the microtube in the reservoir structure and is injected into the via hole during reflow. (h) Device die and reservoir structure separation. (i) Formed TSV in the device die.

With these parameters, a three-via test die was reliably fabricated. Solder flow was completed in a few seconds of reaching the reflow temperature. Fig. 4(a) and (b) shows the protruding solder caps formed on the top and bottom of the device die. Fig. 4(c) shows a cleaved view of the solder via. There is no evidence of voids between the solder and the sidewall. All the solder volume is injected into the via holes, completely emptying the reservoirs. The impedance of the via is below the milliohm lower limit of four-probe measurements: Using the solder resistivity and via geometry gives a value of 0.5 mΩ. Fig. 5 shows that solder-free underpass and feed holes with some flux residue around the second feed hole: Both feed and underpass dies can be reused after cleaning.

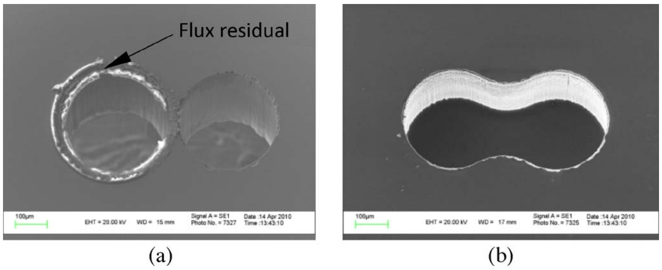


(a)

(b)

(c)

Fig. 4. (a) Formed solder caps on the top of the device die. (b) Formed solder caps on the bottom of the device die. (c) Cleaved view of the solder. $AR \approx 0.7$.



(a)

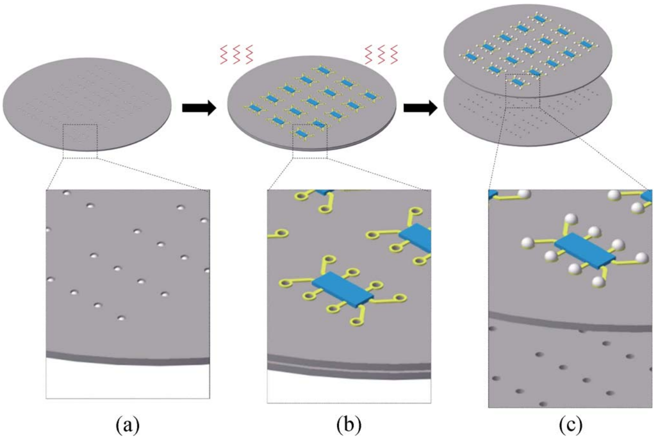
(b)

Fig. 5. (a) Feed holes after reflow. The debris around the second feed hole is flux residual. (b) Underpass after reflow, which shows a very clear surface.

V. CONCLUSION

The presented advanced solder pump for TSV technology has several features that make it practical for batch applications. First, the solder ball loading process occurs before the devices are introduced; automated solder ball placement is therefore much easier. Second, the reusable reservoir structure reduces the cost for batch processing. Third, compared to our previous approach, the advanced solder pump requires no additional area from the device. Hence, this approach provides a method to "print" via-last through-wafer interconnects. The concept is shown in Fig. 6 at the wafer level with via formation in a device wafer accomplished in three steps.

Smaller solder balls would reduce the minimum via size and increase the maximum interconnect density: With 100-μm spheres, 120-μm-diameter vias are possible.



(a)

(b)

(c)

Fig. 6. Novel concept for wafer-level via-last TSV "printing" using the solder pump technology: (a) Reservoir wafer is loaded with solder spheres using an automated ball placement tool; (b) device wafer is temporarily mounted on top of the reservoir wafer, and the wafer sandwich is heated to reflow temperature; (c) solder is transferred to the device wafer and forms TSV after reflow. The now empty reservoir wafer can be reused and reloaded with solder ready for the next device wafer.

Compared to conventional through-wafer via fabrication, this solder pump approach has several significant advantages: 1) No sidewall metallization is needed for the via hole; 2) it is fast, just a few seconds for solder reflow compared to several hours for electroplating; and 3) only standard wafers and fabrication techniques are required, making such an approach accessible to most microfabrication facilities. Furthermore, this approach is not limited to silicon wafers; the reservoir can be made from any substrate that is nonwettable to liquid solder.

REFERENCES

[1] K. Takahashi and M. Sekiguchi, "Through silicon via and 3-D wafer/chip stacking technology," in *VLSI Symp. Tech. Dig.*, 2006, pp. 89–92.

[2] J. H. Wu, "A through-wafer interconnect in silicon for RFICs," *IEEE Trans. Electron Devices*, vol. 53, no. 11, pp. 1765–1771, 2004.

[3] C.-W. Lin and C.-P. Hsu, "Implementation of SOG devices with embedded through-wafer silicon vias using a glass reflow process for wafer-level 3D MEMS integration, Micro Electro Mechanical Systems," in *Proc. IEEE 21st Int. Conf. MEMS*, 2008, pp. 802–805.

[4] J. Tian, J. Iannacci, S. Sosin, R. Gaddi, and M. Bartek, "RF-MEMS wafer-level packaging using through-wafer via technology," in *Proc. 8th EPTC*, 2006, pp. 441–447.

[5] L. L. W. Leung and K. J. Chen, "Microwave characterization and modeling of high aspect ratio through-wafer interconnect vias in silicon substrates," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 8, pp. 2472–2480, Aug. 2005.

[6] J. Gu, W. T. Pike, and W. J. Karl, "A novel capillary-effect-based solder pump structure and its potential application for through-wafer interconnection," *J. Micromech. Microeng.*, vol. 19, no. 7, p. 074005, Jul. 2009.

[7] J. Gu, W. T. Pike, and W. J. Karl, "An operational through-wafer interconnect using a solder pump technique," presented at the 20th MicroMechanics Europe Workshop (MME), Toulouse, France, 2009.

[8] J. Gu, W. T. Pike, and W. J. Karl, "A novel vertical solder-pump structure for through-wafer interconnects," in *Proc. 23rd IEEE Int. Conf. MEMS*, Hong Kong, 2010, pp. 500–503.

[9] R. R. A. Syms, E. M. Yeatman, V. M. Bright, and G. M. Whitesides, "Surface tension-powered self-assembly of microstructures—The state-of-the-art," *J. Microelectromech. Syst.*, vol. 12, no. 4, pp. 387–417, Aug. 2003.

[10] I. Kaban, S. Mhiaoui, W. Hoyer, and J.-G. Gasser, "Surface tension and density of binary lead and lead-free Sn-based solders," *J. Phys., Condens. Matter*, vol. 17, no. 50, pp. 7867–7873, Dec. 2005.

[11] A. Passerone, E. Ricci, and R. Sangiorgi, "Influence of oxygen contamination on the surface tension of liquid tin," *J. Mater. Sci.*, vol. 25, no. 10, pp. 4266–4272, Oct. 1990.