3D INTEGRATION USING SELF-ASSEMBLY AT AIR-WATER INTERFACE

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ABSTRACT

This paper presents the first proof-of-concept 3D integration using self-assembly of chip-scale parts (100 μm thickness). 3D integration is achieved by assembling new parts over previously assembled parts. Assembly proceeds as an assembly substrate is pulled up through an air-water interface and electrical and mechanical bonding is achieved through a solder reflow process. Magnetic fields and temporary Faraday waves are introduced for one-to-one part-to-site registration in proper orientation. The maximum number of layers that can be achieved is simulated and analyzed. Via resistance including the effect of degradation of solder over repeated reflow process is measured.

INTRODUCTION

As microelectronics technology approaches its physical limit of CMOS scaling, prevailing growth driven by a continuous reduction in cost per function cannot be sustained by miniaturization (More-Moore technology) alone. Assembly and packaging area is increasingly undertaking this responsibility, and it is doing so based on the principles of densification of the functions. Functional enrichment (More-than-Moore technology) [1] focuses on 3D integration rather than transistor density alone.

Today's smart electronics (GPS, tablets, smartphones, digital cameras, etc.) consist of digital and non-digital components to provide additional functions and increased performances. Non-digital components (RF/MEMS devices, sensors, actuators, etc.) play an equally important role in cost-effective and value-added systems. Thus, integration of digital and non-digital components in small spaces will be another trend of system miniaturization. Moore's law has ruled scaling down of microelectronics for the past decades. However, components for interfacing with the physical world are non-digital and do not scale down at the same rate of Moore's law. Thus, functional enrichment also known as a More-than-Moore technology gains significance to reach beyond the limit of the conventional More-Moore technology.

An integration of multiple electronic components from different fabrication processes in a single unit is known as system in package (SiP). Compared to 2D (horizontal) SiP, 3D integration (stacked and embedded) is emerging due to its advantages; less power consumption, higher performance, smaller area, lower cost and stacking multiple parts from different fabrication processes, which enables the extension of Moore's law and the delivery of smarter and cheaper electronics. Thus, 3D integration gains importance and is already in use in some domains (cell phones and memory). To fully take advantage of 3D integration, thinner components are preferred.

In addition to 3D integration, system miniaturization is being done using 0050025 chips ($L \times W = 0.2 \times 0.1 \text{ mm}^2$), which has half the height of today's regular micro components (01005 chips, measuring $L \times W = 0.4 \times 0.2 \text{ mm}^2$) [2]. 0050025 chips are highly fragile and today's pick-and-place assembly still has yield issues even with 0201 chips. For assembly with large numbers of small and thin parts, conventional pick-and-place becomes costly and self-assembly is a viable alternative.

Thus, many research groups have developed self-assembly systems, which employ various driving forces such as gravity [3], surface tension [4-6], electrostatic [7] or magnetic force [8-10] and

often require adhesives, liquid solder, shape matching structures or two different liquids [10]. They, however, have lower yield compared to the pick-and-place assembly due to their stochastic nature [11]. Moreover, these assembly methods are not suited for 3D integration.

In [12], we introduced a novel fluidic self-assembly (FSA) of millimeter-scale thin square parts at the air-water interface. Demonstration of high yield using temporary Faraday waves [13, 14], a comprehensive model and experimental support are also presented. In our previous FSA system, parts are assembled in four orientations (0° , 90° , 180° , 270°) due to their square shape. In [15], we extended our fluidic self-assembly (FSA) repertoire to assembling thin square parts with unique orientation through the use of Ni patterns and magnetic fields. Here, we present the first proof-of-concept 3D FSA of 2 mm sized parts (100 μm thick) with experimental data as one of More-than-Moore technologies. The proposed FSA system achieves 3D integration by assembling parts on top of previously assembled parts.

SYSTEM DESIGN AND FABRICATION

Assembly overview

A 3D FSA system (Figure 1) consists of a water container on a linear electromagnetic shaker (Brüel & Kjær Type 4809), a stepper motor (Soyo, SY42STH38-0406A) with the controller (Phidgets, 1062), a substrate and parts floating at an air-water interface. The acceleration uniformity over the vibration table is $\pm 10 \text{ mg}$ or 0.72% as measured using a laser vibrometer (Polytec OFV-534 laser unit and OFV-2500 vibrometer controller) when driven at $80 \text{ Hz}/1.5 \text{ g}$ ($1 \text{ g} = 9.8 \text{ m/s}^2$).

The substrate has preprogrammed hydrophilic binding sites and a self-assembled monolayer (SAM)-coated hydrophobic Au area. The substrate is tilted at an angle of 45° relative to the water surface. Test electrodes are patterned on the substrate to measure the resistance of through-silicon vias (TSVs). To attract Ni patterned parts in proper orientation, rare-earth neodymium iron boron magnets (NeFeB, Grade N40, diameter = thickness = $1/16 \text{ inch}$) are placed beneath each binding site. Accurate magnet-binding site alignment is achieved using photolithographically patterned "magnet templates". Magnets are placed in magnet-sized trenches. Then the magnet template is aligned with the assembly substrate.

Standing wave patterns in a layer of liquid enclosed by a vibrating container are known as Faraday waves [13, 14]. Typical yield loss in FSA is due to lack of control of one-on-one part-to-site registration. In our FSA system, Faraday waves are generated by use of a vertical electromagnetic shaker driven at $80 \text{ Hz}/1.5 \text{ g}$. We avoid multiple parts approaching the same site and guarantee high yield by use of surface waves. Although most parts approach binding sites in proper orientation due to the magnetic field, it is possible that none, multiple or wrongly oriented parts occupy binding sites due to the stochastic character of the approach process. Faraday waves are applied to prevent multiple parts from approaching one site and to achieve one-to-one part-to-site registration in proper orientation [15]. Correctly registered parts experience stronger magnetic force than wrongly oriented ones. Thus wrongly oriented or extra parts are selectively repelled by Faraday waves and other parts have a chance to approach the empty binding sites.

Figure 1. Assembly system. (a) Experimental setup for assembly consists of a water container on a linear electromagnetic shaker, a stepper motor with the controller, a substrate and parts floating at an air-water interface. (b) Design of parts and binding sites. Each part has six via holes and each binding site has six electrodes for electrical measurement.

Figure 2. Assembly process. After assembly of each layer of parts, solder reflow process is needed for electrical and mechanical connection. 3D integration of multiple layers is achievable through a layer-by-layer assembly.

The correctly registered parts are assembled by substrate pull-up (Figure 2(a)). The parts are then mechanically and electrically connected to the binding sites by solder (In/Bi/Sn, 60°C) reflow at 65°C. The magnetic force and the capillary force between parts help part-to-part alignment.

3D integration of multiple layers is achieved by repeating part assembly and solder reflow (Figure 2(b)) processes. Once the first layer of parts is fixed, repeated assembly and solder reflow process achieve 3D multi-layer integration. The maximum number of layers is limited by the magnetic field strength that prevents parts from being withdrawn during substrate pull up.

Fabrication

The fabrication process includes the assembly template fabrication and part fabrication. A combination of photolithography, deep reactive ion etching (DRIE) and metallization is used for the assembly template. As pictured in Figure 3(a), the process starts with DRIE through a photoresist mask on a Si wafer in order to form the assembly sites and the trenches connecting those assembly sites. The depth of the etched region is limited to 70 μm in a timed etch. After that, a metal layer of 10 nm Cr and 100 nm Au is deposited using electron beam evaporation. This metal layer is patterned for electrical interconnect by metal etching.

Figure 3. Fabrication process flow for (a) the assembly template and (b) parts.

The fabrication process for parts is more complicated compared to the assembly template. Through silicon vias (TSV) are employed for electrical connection in the z-direction. An unconventional method is employed for that purpose. The fabrication process is divided into three steps; via formation, Ni pattern deposition and part release. A silicon-on-insulator (SOI) substrate with a device layer of 100 μm is used. The SOI wafer has a lightly doped p-type device layer (100 μm thick, 20,000 – 50,000

$\Omega \cdot \text{cm}$) and highly doped n-type handle wafer (500 μm thick, 0.001 – 0.005 $\Omega \cdot \text{cm}$) which enables seed layer-less electroplating [16].

Fabrication starts with a photolithography step where via locations are defined as illustrated in Figure 3(b). They are etched with DRIE until the oxide layer is reached. The oxide in openings is removed in HF in order to expose the underlying Si layer. Photoresist on the wafer surface is kept throughout the process. TSVs are fabricated by Au electroplating. A 100 nm Au layer is deposited onto the wafer as the seed layer with e-beam evaporation. A Cr adhesion layer is avoided in order to prevent a strong adhesion between TSV and the handle wafer. Metal layer deposited on the top surface is lifted off by removing the photoresist before electroplating. The highly doped handle wafer is used as the conducting medium for electroplating TSV onto Au layer in the hole.

Figure 4. Part with gap between parts. (Left) 6 Au TSVs (diameter = 100 μm) and a Ni pattern (200 × 200 × 13 μm^3) are patterned. (Right) Measured gap between parts is 22 μm . Part size is 2000 × 2000 × 100 μm^3 .

TSV fabrication is followed by the Ni pattern deposition. A metal layer of 10 nm Cr and 100 nm Au is deposited as the seed layer using e-beam evaporation. The wafer is then spin-coated with 22 μm thick AZ 4620 photoresist and patterned by standard photolithography to define 200 × 200 μm square windows. A 13 μm tall Ni layer is electroplated through the exposed Au areas. Cr/Au seed layer used in this process is later removed using the electroplated Ni layer as the mask. Part boundaries are defined in another DRIE step through a photoresist mask. After that, the substrate is left in hydrofluoric acid (HF) in order to release parts from the handle wafer. The released parts are coated with a low-melting point solder (In/Bi/Sn, 60°C) by dip coating. Figure 4 shows a substrate and parts with solder bumps. Thickness of a part including solder bumps is about 120 μm .

RESULTS AND DISCUSSION

The effect of the magnetic field

It is observed that 4 layers of parts are the maximum achievable limit by our experimental setup (substrate thickness: 430 μm = 70 μm deep binding site on 500 μm thick Si wafer, magnet diameter/thickness: 1.56/0.78 mm (grade N40), part size: 2000 × 2000 × 100 μm^3 , Ni pattern size: 200 × 200 × 13 μm^3). Assembly fails if the gravitational force during pull-up is larger than the magnetic force.

Thus, we hypothesize that a critical magnetic force exists that guarantees successful assembly. In our FSA system, the magnetic force on a part is determined by the gap between a magnet and a Ni pattern. The minimum magnetic force is experimentally determined by assembly test at various gap values. The maximum gap that allows assembly is found to be 0.99 mm and a corresponding magnetic force is simulated to be 6.6 μN using COMSOL Multiphysics™. Near the threshold magnetic force of 6.6 μN , assembly becomes vulnerable to inevitable variations such as magnet-to-binding site alignment, part-to-part alignment, Ni pattern

thickness and solder thickness. Thus, assembly becomes more reliable below a gap of 0.99 mm.

Figure 5 shows the decrease of the magnetic force with increasing gap between a magnet and a Ni pattern. The gap between parts after solder reflow is measured to be 22 μm . Thus, the maximum number of layers of parts with successful assembly is predicted to be 4 layers (total thickness $\approx$ 0.92 mm including substrate). This limit can be extended by increasing the magnetic force (larger Ni pattern size, stronger magnetic field, thinner substrate, thinner parts, etc.).

Figure 5. Simulated magnetic force decreases with increasing gap. The minimum magnetic force for successful assembly is 6.6 μN (at 0.99 mm). 13 μm thick Ni pattern is assumed. The total gap between a magnet and a Ni pattern on the 4th layer is 918 μm .

Electrical tests

In the proposed FSA system, assembled parts need to be electrically and mechanically fixed through a solder reflow process. The solder bumps on the first layer go through a repeated reflow process as each additional layer is assembled. Thus, degradation of In/Bi/Sn solder over repeated reflow processes needs to be investigated. Resistance through a solder-coated TSV (diameter of 100 μm) is measured by repeating the reflow process at 65°C for 20 times. The measured resistance does not show any degradation. Mean and standard deviation are 0.08 and 0.003 Ω , respectively.

Figure 6. Assembly results. 4 layers of 2 mm sized parts are assembled on 2 × 2 binding sites.

Next, TSV resistance values are measured after assembling the 1st and 4th layers (Figure 6). Mean and standard deviation of resistance through 4 TSVs in series are measured to be 0.33 and 0.05 Ω . Figure 7 shows the comparison between resistance values of single TSV and 4 TSVs in series. Resistance through 4 TSVs is almost 4 times of a single TSV resistance and has wider deviation.

Figure 7. Distributions of measured resistance through (a) single TSV (Mean = 0.08 Ω , StDev = 0.012 Ω) and (b) 4 TSVs in series (Mean = 0.33 Ω , StDev = 0.051 Ω).

Statistical data from these experiments are limited because of low yield in the fabrication process for the parts (Ni patterns on Au film often peeled off during HF release etch). Assembly is limited to 2×2 binding sites due to lack of good parts.

CONCLUSIONS

The first proof-of-concept 3D multi-layer integration using fluidic self-assembly of chip scale parts (100 μm thick) is demonstrated. 4 layers of parts are assembled through layer-by-layer assembly followed by a solder reflow process for electrical and mechanical bonding.

Thin parts with Au TSVs with diameter of 100 μm are successfully fabricated using electroplating without a seed layer. A Ni pattern on a part interacting with magnetic field guarantees assembly with unique orientation.

The maximum number of layers that can be achieved using the proposed FSA system is determined by the competition between magnetic force and gravitational force on a part. For given conditions, a threshold magnetic force is experimentally established. Then, the limit of achievable number of layers is predicted using simulation and compared with experimental results.

In/Bi/Sn solder shows no degradation over repeated reflow processes. Measured resistance through a single TSV and 4 TSVs in series are 0.08 and 0.33 Ω , respectively.

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