VERTICAL AND HORIZONTAL PARALLEL MOUNTING OF MICRO COMPONENTS ON A SUBSTRATE WITH HIGH SURFACE COVERAGE

Jiandong Fang and Karl F. Böhringer

Department of Electrical Engineering
University of Washington, Seattle, WA, 98195, USA

ABSTRACT

We demonstrate a novel parallel micro assembly process based on both shape recognition and capillary-driven self-assembly in an air environment. Mechanically diced silicon parts with dimensions of 790μm×790μm×330μm are used for proof-of-concept demonstrations. Each part has only one hydrophobic 790μm×790μm face and its other faces are hydrophilic. On a vibrating plate, tumbling parts are captured by cavities having an opening clearance that only admits a single part standing vertically with a 790μm×330μm footprint. The trapped parts are then transferred to a substrate having an array of receptor sites covered with water droplets. Initially the parts are vertically attached, but capillary forces from water condensate turn them to face the substrate with their 790μm×790μm hydrophilic faces. This process assembles micro parts to densely packed 1000 receptor sites in about 2 minutes with a defect rate ~1%. A single batch assembly process achieves 31% surface coverage, and a 2nd batch doubles the ratio to 62%.

1. INTRODUCTION

During the past decade, several parallel micro assembly techniques have been developed and published. These techniques can be grouped into three categories according to their mechanisms to deliver and/or anchor micro components to receptor sites: (1) shape-directed self-assembly [1]; (2) capillary-driven self-assembly [2-6]; (3) electrostatically driven self-assembly [7, 8]. Micro components are usually singulated in rectangular shapes from a substrate by dicing (the last fabrication step), thus they have vertical edges, i.e., the top and bottom surfaces are geometrically identical to any type of receptor sites. To assemble such components, none of the above assembly techniques can effectively avoid uncertainties of face and /or in-plane orientations.

Our previous parallel assembly techniques [9, 10] based on feature recognition required protruding pegs on parts, thus they are not suitable for applications requiring flat part surfaces. Here we report a novel assembly process based on both shape-recognition and capillary-driven mechanisms. This assembly process has the following capabilities: (1) highly dense assembly of peg-free micro components (e.g., useful for assembly of an LED display to achieve good resolutions); (2) process in an air environment; (3) two modes of controlled part mounting: vertical and horizontal; (4) unique face-orienting of parts for horizontal mounting; (5) multi-batch assembly of various types of components, even with same dimensions; (6) high surface coverage on a

substrate achieved by multi-batch assembly. Mechanically diced 790μm×790μm×330μm silicon parts with a single hydrophobic 790μm×790μm face (the opposing face is hydrophilic silicon oxide) are used for proof-of-concept demonstrations.
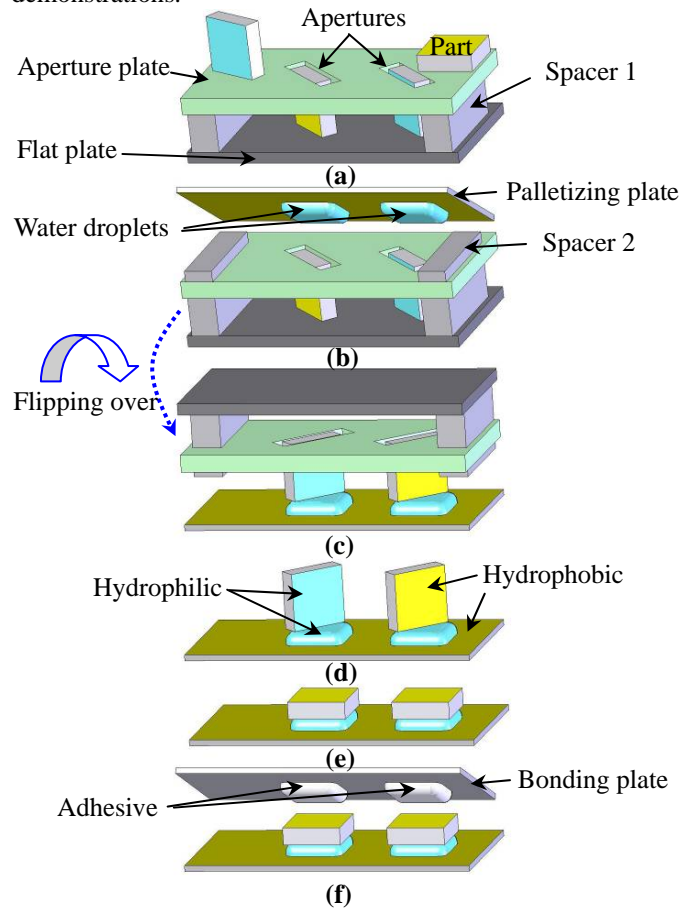

Fig.1. *Assembly process overview. (a) bulk parts fall into apertures vertically; (b) a palletizing plate carrying water droplets is aligned with the aperture plate; (c) the plates are flipped over to transfer parts onto water droplets; (d) parts stand on receptor sites; (e) parts rotate to adhere to the palletizing plate with their hydrophilic oxide face; (f) parts are permanently bonded to a bonding plate via wafer level flip chip bonding.*

2. PARALLEL ASSEMBLY STRATEGY

A typical parallel micro assembly process has two major goals: (1) micro components are delivered to receptor sites with one-to-one registration; (2) micro components contact receptor sites with their bonding faces. To achieve these

goals, we develop the following strategy (Fig. 1, each part has a unique hydrophobic face): first, an aperture plate captures tumbling parts, and each aperture admits exactly one vertically standing part due to geometric constraints shown in Fig. 2; second, a palletizing plate with an array of water covered hydrophilic receptor sites is visually and roughly aligned with the aperture plate and picks up the trapped parts by surface tension of water; third, parts keep vertically attached to the palletizing plate due to the limited volume of water on the receptor sites, and are then laid down on their hydrophilic faces by adding more water on the receptor sites through steam condensation; fourth, water is evaporated by heating, and parts self-align with receptor sites; finally parts are permanently bonded via wafer level flip-chip bonding to a bonding plate.
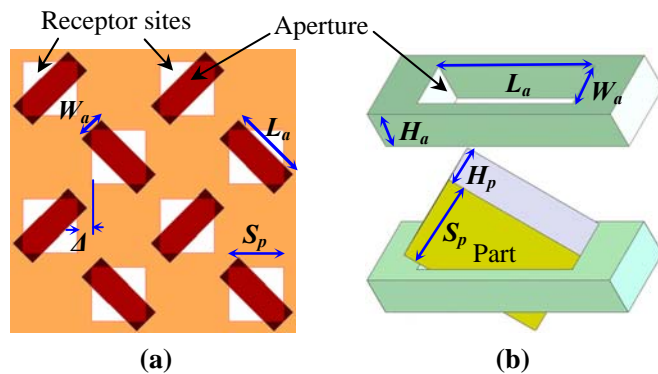

Fig. 2. *Design rules for dimensions of parts, apertures, spacers and receptor sites: (a) a partial view of the overlapped layouts of the aperture plate and the palletizing plate; (b) a diagonally wedged part can be avoided when the aperture length L_a is greater than the diagonal of the part $\sqrt{2}\ S_p$. We use: S_p=790μm, H_p=330μm, L_a=1130μm, W_a=400μm, H_a=330μm, Δ=210μm and H_s= 460μm.*

3. FABRICATION AND SURFACE TREATMENT

Silicon parts are fabricated by mechanical dicing from a 4" silicon wafer with thickness of 330μm. Before dicing, the wafer undergoes the following process steps: (1) a layer of ~4000Å thermal oxide is grown on both sides by a wet oxidation process at 1100°C for about 30 minutes; (2) a layer of TiW/Au (50Å/1000Å) is sputter deposited on one side. Then the silicon wafer is mechanically diced into 790μm square parts. Diced parts are subsequently cleaned in acetone, isopropanol (IPA), de-ionized (DI) water in a sonicator, and then collected to be baked dry on a piece of filter paper. Finally bulk parts are soaked in a 0.1mmol alkanethiol $CH_3(CH_2)_{11}SH$ solution (ethanol is the solvent) overnight for a hydrophobic self-assembled monolayer (SAM) to selectively cover the Au surfaces. All the other part faces remain hydrophilic.

A 4" **aperture plate** having 1000 apertures is fabricated from a 330μm thick oxidized silicon wafer by a deep reactive ion etching (DRIE) process. First, photoresist AZ4620 (Clariant) is deposited and patterned on the silicon substrate with the following recipe: (1) singe the substrate at 100°C for 1 minute; (2) spincoat AZ4620 at 500 RPM for 8 sec, and then 1500 RPM for 40 sec; (3) bake at 70°C for 5 minutes, and then 100°C for 5 minutes; (4) expose with a transparency mask for 30 sec on an ABM IR aligner; (5) develop in a solution of AZ400K : DI water = 1 : 2 for 1.5 minutes; (6) spin dry the substrate; (7) hard bake AZ4620 at 110°C for 15 minutes. Second, a piece of dicing blue tape covers the back side of the substrate, and then the substrate is soaked in a buffered oxide etchant (BOE) solution for about 8 minutes to completely remove exposed thermal oxide in thickness of ~4000Å. The oxide on the back side is left to be an etch stop for a later DRIE process. Third, the substrate is run in a DRIE process for about 110 minutes, and then soaked in a BOE solution to remove oxide on the backside, thus through-hole apertures are formed. Finally, photoresist is stripped with acetone, and then the substrate is cleaned in IPA and DI water.

A **glass palletizing plate** is coated with patterned thiolated Au. First, a layer of TiW/Au (50Å/1000Å) is sputter deposited on the glass substrate. Second, photoresist AZ1512 is spincoated and photolithographically patterned to expose an array of 790μm square gold areas. Third, exposed Au and TiW underneath are subsequently etched in an Au etchant (TFA type) and H_2O_2. Finally photoresist AZ1512 is stripped with acetone and the substrate is cleaned in IPA and DI water. The cleaned substrate is soaked in a 0.1mmol alkanethiol $CH_3(CH_2)_{11}SH$ solution for Au areas to become hydrophobic by adsorbing a SAM, while the exposed glass squares are used as hydrophilic receptor sites.

A photolithography process leaves an array of photoresist AZ4620 790μm squares on a **glass bonding plate**. The recipe for AZ4620 is the same as that for the above aperture plate.

4. EXPERIMENTAL IMPLEMENTATION

We accomplish parallel mounting of micro components on a substrate with three major steps: positioning, orienting and bonding of micro components, i.e., bulk micro components were first distributed to an array of receptor sites, and then uniquely face-oriented, and finally permanently bonded to a bonding substrate. The following paragraphs describe the process details.

Bulk parts are first distributed by vibration into an array of apertures. The experimental setup is shown in Fig. 3. The vibrating stage is a 4-inch aluminum plate glued to the center of the diaphragm of a subwoofer, and the subwoofer is driven by AC voltage signals from a function generator. The plates with 1000 apertures are mounted on the aluminum plate. When the vibrating stage is turned on, a paper funnel carrying about 3000 bulk parts is scanned across the aperture plate to release parts, thus parts are uniformly fed. On the vibrating (driving frequency = 50Hz) plate, parts tumble randomly until falling into the apertures. Due to geometric

constraints (Fig. 2), one aperture adopts exactly one part, and the part stands vertically with a 790μm × 330μm footprint. Literature [11] reported several vibrating strategies to orient agitated parts. The vibration amplitude is controlled to be less than 500μm so that the trapped parts stay in place and other free parts keep tumbling randomly until being trapped. Finally redundant parts are easily wiped off since trapped parts make a flat surface on the aperture plate. We run the trapping experiment 6 times with 3000 bulk parts, and observe yields ranging from 98.5% to 99.8% in about 2 minutes (Fig. 4).
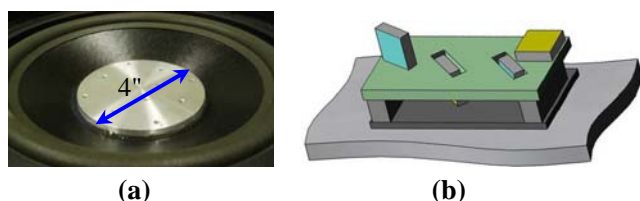

Fig. 3. *Experimental setup for parts falling into apertures:* **(a)** *a 4" aluminum platform mounted at the center of a subwoofer diaphragm;* **(b)** *plates mounted on the vibrating aluminum platform, where parts tumble randomly until falling into apertures.*
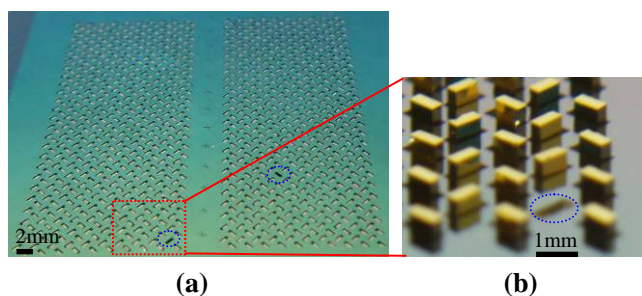

Fig. 4. *Experimental results of parts falling into apertures vertically:* **(a)** *an aperture plate with 1000 apertures, two apertures are empty (yield = 99.8%);* **(b)** *parts protruding out of the aperture plate when the spacers (Fig. 1a) are removed.*

Trapped parts are then transferred to a glass palletizing plate via temporary bonding by capillary forces. The palletizing plate has an array of hydrophilic receptor sites and hydrophobic thiolated gold background. A dip coating process leaves water droplets on the receptor sites (Fig. 5a-b). The part transfer process is schematically shown in Fig. 1b-d. The palletizing plate is placed on top of the aperture plate with two 150μm thick spacers between them, and two plates are roughly aligned for each water droplet to oppose a part directly. These spacers prevent water droplets from contacting the hydrophilic aperture plate and parts, which must be avoided because water can cause parts to be stuck in the apertures by capillary forces. When the stack of plates is flipped over, parts fall down and stand vertically on the receptor sites (Fig. 5c and f), i.e. parts have been vertically assembled.

To assemble parts horizontally with 790μm × 790μm footprints, we introduce water steam to condensate on the surfaces (droplet-wise and film-wise condensation respectively on hydrophobic and hydrophilic surfaces, see Fig. 5d), thus the receptor sites gain more water. Since water
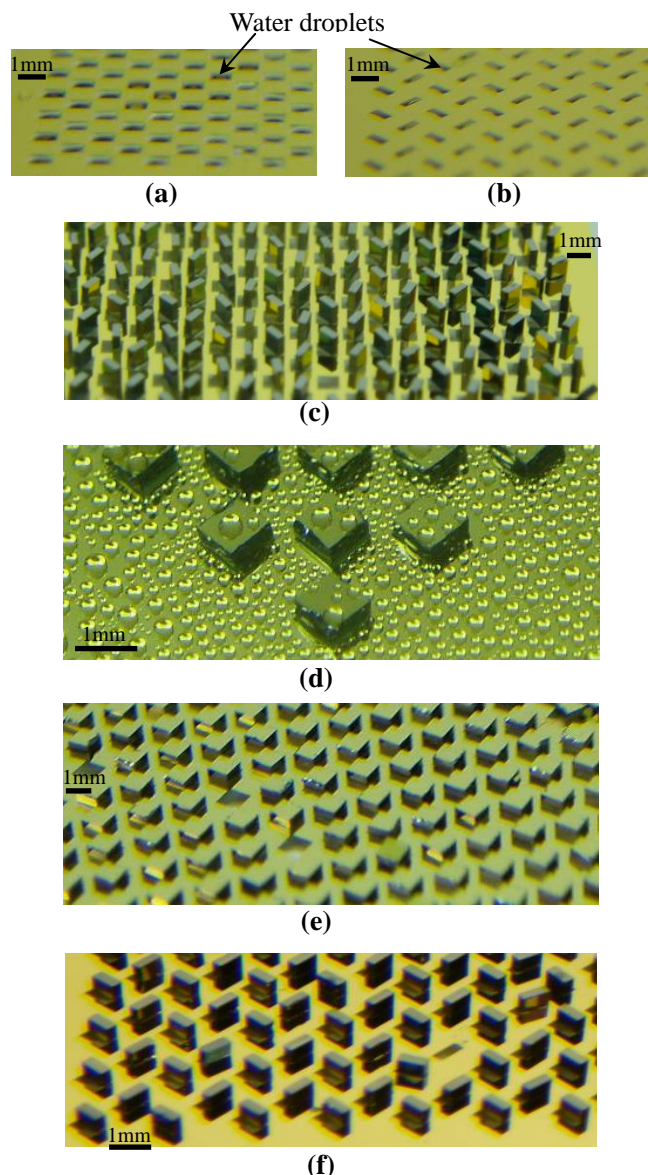

Fig. 5. *Parts transferred to a palletizing pyrex plate via water droplets:* **(a)** *a partial view of an array of square hydrophilic receptor sites covered with water droplets;* **(b)** *a partial view of an array of rectangular (same size as the part edge) hydrophilic receptor sites with covered water droplets;* **(c)** *parts are transferred and standing vertically (see Fig. 1d);* **(d)** *water steam condensation is introduced on the palletizing plate, where steam forms film-wise and droplet-wise condensation respectively on hydrophilic and hydrophobic areas;* **(e)** *parts attached to receptor sites horizontally after steam condensation, and the only hydrophobic Au surface faces outward;* **(f)** *parts assembled vertically on receptor sites of Fig. 5b without steam condensation.*

condensate favors the hydrophilic oxide face of each part and the hydrophilic receptor sites, water wetting lines on the

hydrophilic part faces are higher than those on the hydrophobic part faces. This height difference brings about a capillary torque on each part. The longer the steam condensation time, the greater the height difference and the greater the capillary torque. When the capillary torques are greater than reversely directed gravitational torques on parts, net torques drive parts to rotate to face the receptor sites with their hydrophilic oxide faces (Fig. 5e). A slight agitation on the palletizing plate can cause parts to rotate with less water condensate because vibration brings about additional torques to overcome gravitational torques. Finally excess water is evaporated by heating at about 70ºC and parts self-align with high precision to minimize interfacial energies. The less water remains underneath the parts, the more accurate the alignment becomes.

Finally parts are permanently bonded to a glass bonding plate with patterned AZ4620 squares (Fig. 6a). When the bonding plate is in contact and aligned with the palletizing plate, parts are bonded by reflowed AZ4620. High surface coverage ratio of $S_P^2/2(S_P+\Delta)^2 = 31\%$ is achieved by a single batch transfer (Fig. 6b). By using the same plates (aperture, palletizing and bonding plates), and offsetting the alignment between the palletizing plate and the bonding plate by a row or column ($S_P+\Delta$), a 2nd batch transfer increases this ratio to 62% (Fig.6c). Melting solder is another option for the permanent mechanical bonding together with electrical connections.
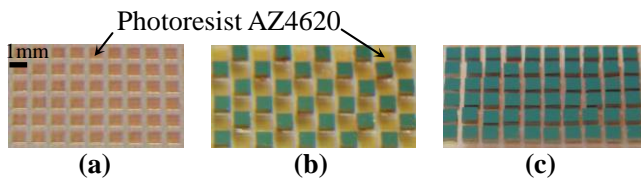

Fig. 6. *Permanent bonding of parts:* **(a)** *an array of receptor sites covered with photoresist AZ4620;* **(b)** *parts bonded by the reflowed AZ4620 after one batch transfer (Fig. 1f);* **(c)** *parts bonded by reflowed AZ4620 after 2nd batch transfer.*

5. CONCLUSIONS AND DISCUSSIONS

We have demonstrated a parallel micro assembly process based on both shape recognition and capillary-driven self-assembly in an air environment, which assembles parts in a vertical or horizontal mode to densely packed receptor sites with a defect rate of ~1%. The vertical mode is useful for edge-emitting or vertical cavity surface-emitting laser (VCSEL) components, laser beam routing, RF MEMS components etc. The horizontal mode can be applied to assembly of LED displays, RFID chips, and other types of flat micro components. Additionally, the multi-batch assembly capability of this assembly process enables packaging single or multiple types of micro components with high surface coverage ratios on a single substrate.

6. ACKNOWLEDGEMENTS

7. REFERENCES

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