Optimization of a Capillary-Driven Self-Assembly Process

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Abstract: Fluidic self-assembly using capillary forces has shown great potential for the manufacture of heterogeneous and three-dimensional microsystems because of its self-aligning and parallel assembly nature. Alignment of the parts to their binding sites needs a high degree of accuracy especially in applications with high interconnect density. However, disturbance forces and part tilting threaten a correct assembly. The purpose of this work is to optimize the alignment accuracy of the part by varying the assembly parameters. Silicon parts are assembled onto a glass substrate in an aqueous environment. A hydrophobic heat-curable adhesive is used as a mechanical bond between the parts and the substrate. The capillary forces between the hydrophobic components act to align the parts. Vertical vibration is used for tilt correction, and a frequency of 30 Hz is shown to be most effective. In addition, part alignment has been measured as a function of adhesive volume. Lateral misalignment is shown to increase with larger adhesive volumes.

1. INTRODUCTION
Currently, microelectronic components are fabricated using primarily two-dimensional fabrication technologies such as photolithography or etching. The two-dimensional components are integrated using strategies based on pick-and-place robots [3]. As smaller sizes and higher speeds become increasingly important, these robots become unfit for the job. They rely on a slow serial assembly process and are often unable to handle small parts due to surface forces [7]. Self-assembly techniques offer the opportunity to bypass the slow serial assembly of microcomponents for a massively parallel approach. Self-assembly makes the production of wafer-scale 3D microelectronics with high interconnect density realizable.

One self-assembly method showing potential for high density applications is capillary-driven fluidic self-assembly. Surface energy minimization will drive hydrophobic materials to attract each other in an aqueous environment. Figure 1 illustrates the fluidic self-assembly concept. The process provides for self-alignment and a parallel assembly [6]. This project focuses on assembling parts to a temporary substrate. In future applications, the parts will be transferred to the final substrate.

A highly accurate alignment of parts to their corresponding binding sites is extremely important, especially for high interconnect density applications. Different factors in the assembly design will affect the alignment of parts. Parts often assemble to the substrate in a vertically tilted fashion because it represents a local energy minimum. This results in additional misalignment of the part to its binding site. Vertical vibration and the consequent surface water waves have been shown to correct this tilt [1]. An example correction is shown in Figure 2. But, an ideal vibration technique still needs to be developed.

![Figure 1](image-url) - When the hydrophobic binding site makes contact with the adhesive, surface energy minimization self-aligns the part.
2. MATERIALS AND METHODS

In the following experiments, multiple parts are assembled onto an assembly template using the capillary forces of the adhesive. The assembly parts are square with dimensions $5\text{mm} \times 5\text{mm} \times 0.1\text{mm}$. Each part contains a hydrophobic binding site that is rectangular with dimensions $4.6\text{mm} \times 3.2\text{mm}$. Some binding sites were designed with rounded corners of radius $1.1\text{mm}$. The binding sites are attracted to the adhesive in an aqueous environment. The substrate has corresponding binding sites of the same size and shape. Rectangular binding sites were chosen over square binding sites because they have a more specific binding orientation, which gives more flexibility for future circuit design of the parts.

2.1 Fabrication

The assembly template is fabricated using a 4” silicon or glass wafer. The basic process is shown in Figure 3. Binding sites are patterned using photolithography coupled with Cr/Au evaporation and lift-off [1]. A self-assembled monolayer (SAM) of thiol molecules is assembled to the gold binding sites by soaking the wafer in 1 mM dodecanethiol in ethanol overnight. The thiol molecules make the binding sites more hydrophobic with a water contact angle of 110 degrees [7]. Parts are fabricated similarly without the addition of a thiol SAM. Gold alone has a water contact angle of 70 degrees when exposed to the lab environment, and this hydrophobicity will suffice [2]. A grinding process from the back side of the wafer thins the silicon to 100 µm, before dicing the wafer into individual parts.

2.2 Self-Assembly Process

The adhesive used for assembly is hydrophobic and heat curable. It is composed of 97% wt. triethylene glycol dimethacrylate as monomer and 3% wt. benzoyl peroxide as a thermal initiator [2]. In the final scheme, the adhesive is deposited on the binding sites by dip coating. The substrate is immersed in a container with a layer of adhesive under a layer of water. Then the substrate is pulled out through the water. Due to surface energy minimization the adhesive will only remain attached to binding sites. In the next step, the parts are introduced to the substrate, and self-assembly occurs due to surface energy minimization.

![Figure 2. On the left, a surface wave provides needed energy for tilt correction. The right shows a part before and after vibration.](image1)

![Figure 3. Fabrication process for substrates and parts.](image2)
The assembly process in the experiments of this paper is more manual. The effect of assembly parameters is being studied, and those parameters need to be controlled accurately. The substrate is immersed in water, and the adhesive is deposited on the binding sites using a micropipette. The parts are released near their appropriate binding site using tweezers, and assembly occurs due to surface energy minimization. The adhesive is then cured by heating the water to 70 °C for 2 hr.

2.3 Part Vertical Tilting Experiments

Parts are assembled to a substrate, and vibrated in 4mm height of water for 2 min on a vertical vibration stage. A function generator defines the vibration, and an accelerometer measures the acceleration. The parts are imaged before and after vibration with a high-speed camera. Various frequencies and amplitudes are tested. The experimental setup is shown in Figure 4.

2.4 Part Horizontal Alignment Experiments

We studied the effects of adhesive volume, vibration, and binding site shape on the horizontal alignment of the parts with their corresponding binding sites. Horizontal alignment is defined by two orthogonal directions and rotation from the center of the part. The first trial of assemblies included 25 sites with varying volumes of adhesive being used. The assemblies in the second trial were vibrated at 30 Hz with an amplitude of .74 mm for 2 min prior to curing. The parts are assembled on a glass substrate, cured, inverted, and imaged on the microscope.

Because the part and substrate are in different focus planes, two images must be captured. Image processing software is then used to merge the photos for analysis. An example is shown in Figure 5.

In these experiments, we study the rotation with respect to the binding site center and shifts in the x and y directions only. The vernier scale is used to determine the distances between the corners of the part and the binding site. The rotation of the part about its center is extracted. Undoing the effects of rotation, the simple misalignments in the x and y directions can be calculated. The overall shift is found by Pythagorean Theorem.

![Figure 4. Setup for tilt and alignment experiments.](image-url)
3. RESULTS AND DISCUSSION

3.1 Part Vertical Tilting

Figure 6 shows the tilt correction of several assemblies for different amplitudes and frequencies of vibration. There is no apparent trend for the magnitude of the vibration. However, 30 Hz is the most effective vibration frequency at correcting the tilt of the assemblies. Surface Evolver simulations predicted a resonance frequency near 40 Hz [5]. The correction process is not sensitive to specific amplitude values as long as they lie within a practical range.

3.2 Part Horizontal Alignment

Regardless of vibration, a general trend of increasing misalignment with an increase in adhesive volume can be seen in Figure 7. The alignment for the lower three adhesive volumes was improved when vibration was used prior to curing. There was little effect on the alignment for the larger three volumes. Previous models have shown reduced restoring forces for large adhesive volumes [4]. The reduced restoring forces explain the increased misalignment. The reason may be that vibration disturbs the parts, and the larger volumes of adhesive are unable to realign the part.

A simple model may explain the poor alignment for one and three microliter droplets of adhesive. The adhesive is considered to be a cylinder with increasing diameter and diminishing height on top of a binding site with only gravity and surface forces acting on it. A minimum of 2.1µl of volume for the adhesive droplet is required to cover the binding site completely. Consequently, difficulty for a 1 µl drop to coat the entire binding site homogenously is predicted. A 4.4 µl droplet is needed for the diameter of the cylinder to match that of the binding site diagonal. This may indicate problems with the 3µL droplet as well.

![Figure 6. Tilt correction at various frequencies and amplitudes. The correction is greatest at 30 Hz.](image)
For all experiments, misalignment was greater in the x-direction than y-direction. Figure 8 shows the trend and defines x and y misalignment. However, based on theory, a greater misalignment in the y-direction was expected. A displacement in the x-direction exposes more hydrophobic area. Thus, the restoring forces are greater in the x-direction. This unexpected trend may be explained by tilting. Tilt occurs more often along the x-axis due to a smaller diameter of adhesive to support the part. If the part is considered to be anchored on one side of the tilt, the y-axis is also able to provide a greater restoring torque. The increased tilt along the x-axis creates the additional shift in that direction.

When adhesive is coated on the rectangular binding sites, it does not reach the square corners effectively. Parts with rounded corners were designed to correct for this problem. The effects are shown in Figure 9. Without square corners, the part is unable to pin itself to the substrate corners due to stronger local energy minima resulting in a large rotational misalignment.

Increasing adhesive volumes result in a significant increase in rotation for rounded parts. It has little effect on parts with square corners.

![Figure 7. Part misalignment for different adhesive volumes.](image1)

![Figure 8. Misalignment in the x and y directions.](image2)

![Figure 9. Rotational misalignment for square and rounded binding sites.](image3)

### 4. CONCLUSION

The effects of frequency and amplitude of vibration on part tilt correction are explored. Vibration is shown to improve alignment of parts, especially with small volumes of adhesive. Misalignment is found to be greater in the axis that tilt occurs more frequently in. Rounded binding sites do not align as effectively as rectangular binding sites.

### REFERENCES


