Directed Self-Assembly of Microcomponents Enabled by Laser-Activated Bubble Latching

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Supporting Information

**ABSTRACT:** This article introduces a method for microscale assembly using laser-activated bubble latching. The technique combines the advantages of directed fluidic assembly and surface tension-driven latching to create arbitrarily complex and irregular structures with unique properties. The bubble latches, generated through the laser degradation of the tile material, are created on the fly, reversibly linking components at user-determined locations. Different phases of latching bubble growth are analyzed, and shear force calculations show that each bubble is able to support a tensile force of approximately 0.33 μN. We demonstrate that by exploiting the compressibility of bubbles, assembled objects can be made to switch between rigid and flexible states, facilitating component assembly and transport. Furthermore, we show reconfiguration capabilities through the use of bubble hinging. This novel hybrid approach to the assembly of microscale components offers significant user control while retaining a simplistic design environment.

1. INTRODUCTION

Directed assembly methods, such as robotic pick-and-place, have been the essential manufacturing process for constructing complicated multicomponent systems on large scales. These include methods that require some form of energy input into the system, such as the robotic or manual assembly of buildings and cars. Once the sizes of the components reach the submillimeter scale, these serial assembly methods begin to become prohibitively slow and expensive because of the need for high positioning accuracy and the presence of obstructive adhesion forces. Self-assembly techniques that are driven by a system’s tendency to reach an equilibrium state, termed static self-assembly, represent an alternative that overcomes the limitations of serial assembly on the micro- and nanoscales.

Surface tension forces are frequently used as a latching method for self-assembly on the microscale. In such systems, a liquid–gas interface will tend to a low-energy configuration by minimizing its surface area. In early work, components were placed in a large water reservoir and assembled on the basis of the geometric properties or wettability characteristics of their faces. Subsequently, droplet latching techniques were developed as a more targeted assembly approach. Small liquid droplets of solder, resin, and water were used to make site-specific connections between components. These two-phase methods have achieved highly accurate alignment, alignment in specific orientations, and the formation of electrical networks. Using large substrates as receptor platforms, assembly through surface tension techniques can be parallel and therefore potentially faster and cheaper than directed assembly approaches. Thus far, surface tension has primarily been employed to achieve self-assembly, but it has several drawbacks. Assembly is achieved probabilistically; therefore, the assembly yield is not yet as high as that of deterministic approaches. Additionally, in most cases the final structure’s shape and size are critically constrained by the initial design and the number of subelements used in the experiment, making arbitrary structures difficult to generate.

Recent directed fluidic assembly techniques such as railed microfluidics and dynamically programmable fluidic assembly, in which the fluids is the main force for manipulating components, exploit microscale flows to circumvent adhesion problems of other microscale directed assembly methods and provide the user with more control than self assembly techniques in the generation of structures. Unfortunately, the latches used in these cases, along with the surface tension-based methods mentioned previously, all share characteristics that restrict the level of control given to the user. For example, the latches must be predefined during the fabrication process and are permanently on during use. This restricts the assembly of individual pieces to linking at specific locations. In addition, the quasi-permanent nature of the latches restricts the ability to reconfigure structures once they are assembled. Some work has been done to add a switching capability to soldering sites using microheaters. In that work, the switching mechanism was integrated on a large substrate, and there was no switching capability on a component-to-component level.

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In this article, we introduce laser-activated bubble latching, a new directed self-assembly method that combines surface tension-driven self-assembly with directed fluidic assembly and provides a much higher level of control than other latching methods. As illustrated in Figure 1, bubble latches are created at generation hubs on SU-8 microtiles by the user through directed laser heating at any time postfabrication (Movie S1). The tile must be fabricated using a hydrophobic material to facilitate latching between it and the bubble. This process allows the components and the hubs to be designed in a general scheme while giving the user control over the placement of the actual latches, allowing the user to treat each hub as a “switch” that activates latching at arbitrary times and locations. The fluidic properties of bubble latching also facilitate greater structural flexibility of an assembled structure. We demonstrate a controlled disassembly approach to creating arbitrary structures that are not constrained by the initial component design. We explore the growth process of the bubbles and the maximum latching force of these bubble latches as a means of understanding this system. The maximum latching force was found to be in a range that enables structural integrity while also facilitating reversibility. Finally, we exploit the compressibility of the bubbles to induce rigid-to-flexible transitions of assembled objects, allowing for large deformations without unlatching, and demonstrate that the basic components can be quickly and deterministically reconfigured by using the bubble latches as hinges.

2. MATERIALS AND METHODS

2.1. Fabrication. The 500 × 500 μm² SU-8 microtiles and the poly(dimethylsiloxane) (PDMS) channels were fabricated with standard photolithography techniques. Molds were made by spinning an SU-8 2050 photoresist (Microchem) on silicon wafers at 1900 rpm for 30 s to obtain a 90-μm-thick film. The wafers were then soft baked at 65 °C for 2 min and at 95 °C for 10 min, patterned through a chrome photomask using the ABM contact aligner at the Cornell Nanoscale Science and Technology Facility, and hard baked at 65 °C for 2 min and at 95 °C for 10 min. After cooling to room temperature, SU-8 was developed in a solution of SU-8 developer. A 10:1 ratio of PDMS (Sylgard 184) base to curing agent was poured over the SU-8 mold and cured at 80 °C for 2 h. A 1.9-mm-diameter punch was used to make a hole at the inlet of the microchannel structure to facilitate the placement of tiles, and a 0.8-mm-diameter punch was used to create the holes at all other fluidic ports (Figure 2a). PDMS and the glass slide were plasma treated for 30 s and permanently bonded. Because the microtiles tended to get stuck on the hydrophobic PDMS surface, the channels were used immediately after bonding to maintain the hydrophilic property of the PDMS.

For microtile fabrication, Omnicote, an organic polymer solution, was first spin coated onto a silicon wafer at 3000 rpm for 30 s and baked at 200 °C for 1 min. SU-8 2025 was spin-coated on top of this at 2500 rpm for 30 s to achieve a film thickness of 30 μm. This was then exposed and developed using standard procedures as stated previously. To create the hubs to confine the bubbles, a second layer of SU-8 2025 was then spin coated onto the wafer at 2000 rpm to achieve an additional thickness of 30 μm and again exposed and developed. Finally, the wafer was placed in a solution of Microposit MF 321 for 24 h to dissolve the Omnicote layer. The released tiles were then stored on a sheet of Whatman filter paper until use.

2.2. Experimental Technique. An inverted microscope mounted with a CCD camera ( pixeLINK ) was used to record videos of the experiments at 14 frames per second. A 0.5-mm-diameter metal rod bent into an L shape was used to pick up individual tiles. Its tip was wetted with DI water and placed in contact with a tile. The tile is picked up via surface tension and then inserted into the microfluidic chamber. Because of the different geometry between the top and bottom surfaces of the tiles, they must all be inserted with the same side facing up. This was done by inspecting the tile’s reflection under white light and choosing to pick up tiles only in the correct orientation. The microfluidic chips were placed upside down with the PDMS layer below the glass slide for the experiments because of sticking problems observed between the tiles and the PDMS (Supporting Information). The bubbles were created through heating the tiles with a UV laser (40 mW, 405 nm) directed at the hubs. Tygon tubing was used to connect the inlet and all outlets to syringes, and syringe pumps were used for flow injection.

3. RESULTS AND DISCUSSION

3.1. Bubble Formation and Controlled Disassembly of Components. Bubble generation hubs in the form of 100-μm inner diameter, 125-μm outer diameter SU-8 rings act as walls to confine the bubbles. As the SU-8 absorbs the laser energy, its temperature rises and eventually reaches the degradation temperature of 380 °C, where carbon dioxide, carbon monoxide, and other gases are generated. When confined in water, the gases produced from the etched SU-8 form a bubble. The bubble latches to the SU-8 because of its surface hydrophobicity. As the laser continues to heat the tile, the water near the bubble may also evaporate if it reaches the boiling temperature.

As Figure 2 shows, we use the ability to place individual bubble latches arbitrarily in order to realize a controlled disassembly approach for creating complex structures with simple flow controls. The tiles are first assembled in the chamber by injecting flow through the top and drawing it out through specific ports on the bottom and sides of the chamber. With some minor tapping
on the microfluidic chip, the fluid flow pushes the tiles into packed arrays. Laser-activated bubbles are then created between specific tiles, both linking them and securing them in place because of the additional adhesion between the bubbles and the chamber floor. At this point, the flow directions of the ports are simply reversed, and unconnected tiles become released, leaving behind the assembled structure (Movie S2). We demonstrate the creation of “hanging” structures with a carved out interior (Figure 2b), multiple structures created in parallel (Figure 2c), and multistep assembly to create voids, as shown by a stick figure (Figure 2d). The ability to assign arbitrary latching locations uniquely enables the creation of these complex structures (i.e., with voids and carved out regions), in contrast to other directed fluidic assembly techniques where structures must be built in a bottom-up fashion.

3.2. Characterization of Bubble Growth and Latching Strength. The growth behaviors of bubbles both confined within the hubs and unconfined are compared in Figure 3. For each test, we found the frames at which the laser is turned on and also when the tile reaches the degradation temperature, accompanied by a sudden burst of light. In all cases, after being exposed to the laser, SU-8 reaches its degradation temperature after about 3 s. This creates a small deformed region on the tile that is visible if the laser is turned off. The images following this frame are analyzed in Matlab using custom code to mark and calculate the diameter of the bubble. The bubble diameters and the corresponding frame numbers are collected and plotted in Excel. We found that the growth of the bubble can be divided into two stages, as illustrated by Figure 3. At first, the bubble expands steadily until it reaches about 50 μm in diameter, at which point it comes in contact with the PDMS surface. This contact changes the interfacial energies, leading to a second stage where the bubble spreads out rapidly, representing a change in the bubble geometry from a spherical shape to cylindrical. When confined inside the hubs, the sudden expansion is stopped by the ring borders at around 100 μm in diameter. When the bubble is generated in the center of the tile and therefore unconfined, it continues to grow beyond 100 μm. The bubble growth times, shown in Figure 3b, are affected by minor changes in external conditions such as the angle of the laser light incident on the surface and the slight movement of the tile when it is excited by the laser and therefore vary from 5 to 30 s. Conversely, the sizes of the bubbles at the different transition points remained consistent throughout all experiments and are marked by dashed lines in Figure 3b (Supporting Information and Figure S1).

Despite some inconsistencies in the growth time, an analysis of the bubble size as a function of time can still produce a reasonable characterization of the volumetric growth rate. In Figure 3b, the diameter growth data before the sudden expansion was averaged and fitted to an equation of the form \( D = \alpha t^{3/12} \), where \( D \) is the bubble diameter, \( t \) is the time, and \( \alpha \) and \( \beta \) are empirical values. The average diameters were then divided by their respective coefficient \( \alpha \) to normalize the data. Finally, the first eight normalized data points from each set were fitted to weigh the sets equally and are plotted in Figure 3b. Through this analysis, we find \( \beta = 0.3343 \), which suggests that the bubble diameter increases proportionally to approximately \( t^{1/3} \) and that the volumetric growth is approximately linear with time. This finding matches recent measurements of laser-induced bubble growth on metal pads, though we note that in our system bubbles are produced from material degradation instead of liquid vaporization.

Several unknowns including the pressure inside the bubble, the rate at which the tile material is degraded, the temperature profile, and the interfacial tensions of our water—gas—SU-8 system preclude us from calculating the bubble volume using solely its observed diameter. In spite of this, a close estimate can be produced by recognizing that because the hub layer of SU-8 is 30 μm tall the bubble should also be 30 μm tall when it makes contact with the channel. This, coupled with the fact that each bubble grows to 50 μm in diameter at the time of contact, suggest that the bubble is close to hemispherical in shape. Therefore, the volume can be approximated as \( \pi D^3/12 \). Measurements have shown that the contact angle of an air—water interface on SU-8 is close to 90°. Even though the gases in the bubble do not have the same composition as air, this result shows that the surface energy of this system behaves similarly to that of air—water systems. A current limitation of the work is that the tiles are damaged during the creation of bubbles and therefore each tile...
Figure 3. Analysis of bubble growth dynamics (Figure S1). (a) The bubble growth process showing (1) the tile reaching the degradation temperature (time = 0), (2) the bubble growing to 50 μm before the sudden expansion, (3) the expansion stopping at 100 μm for confined bubbles, and (4) the expansion growing beyond 100 μm for unconfined bubbles. The black arrows point to the bubbles. (b) Graph of bubble growth, showing 9 tests out of 34, representing the range of growth times. Numbers on the right represent the bubble sizes at various transition points during growth and correspond to the numbers in the images. (c) For each experiment, the data points before the sudden expansion are averaged and fitted to a power function. The average values are then normalized by their respective coefficient and plotted, showing a radial growth proportional to time to the one-third power. Error bars represent one standard deviation.

Figure 4. Breaking force measurements for bubble latches. (a) Sequence of images showing tiles linked by one bubble being pulled apart and ultimately unlatching. (b) Side-view schematic of the flow profile over tiles used to estimate the shear force. (c) Plot of the maximum flow rate and calculated force for tiles connected by zero, one, two, or three bubbles. The data well matches the expectation that n bubbles can support n times as much force as one bubble latch. The error bars represent one standard deviation.

Figure 4b, the Reynolds number is on the order of 1. This, along with the simple channel geometry, allows us to assume that the flow over the tile takes a Poiseuille flow profile (Figure 4b) of the form

\[ \nu = \frac{3Q}{2A_{c,t}} \left[ 1 - \left( \frac{y}{H} \right)^2 \right] \]

where \( H \) is 15 μm, half the distance between the tile surface and the channel ceiling, \( y \) is the vertical position variable defined in Figure 4b, \( A_{c,t} \) is \( 2.4 \times 10^5 \text{ μm}^2 \), the cross sectional area of the channel minus the cross sectional area of the tile, and \( Q \) is the flow rate. This can then be related to the viscous shear force \( F_{v|y=H} \) on the tile using

\[ F_{v|y=H} = \mu \left( \frac{dv}{dy} \right) A_t \]

where \( A_t \) is 0.25 mm², the area of the face of the tile. Evaluating this equation, we find \( F_{v|y=H} = 0.035Q \) where \( Q \) is in μL/min and \( F_v \) is in μN.

Experiments were performed with one, two, or three bubbles latching the tiles. With no latching, we find that a force of about 60 nN is required to overcome the friction between the tile and the channel wall to move the tile. By subtracting this static friction \( F_0 \), we find that one bubble is able to support a maximum force \( F_{max} \) of about 0.33 μN. When multiple bubbles are used, they act in parallel; therefore, we anticipate latching with \( n \) bubbles to result in a maximum force equal to \( nF_{max} \). The experimental
Relation between the maximum breaking force and the number of bubbles is plotted in Figure 4c and shows good agreement with the linear estimate. This study demonstrates that the user is able to adjust for the latching strength of the system through managing the number of bubbles generated. From these results, we can perform a nondimensionalization of $F_{\text{max}}$ using the equation $(nF_{\text{max}})/F_s$. Values greater than 1 indicate that the bubble system should be able to overcome the frictional force of the cargo. In this instance, we obtain a value of 5.5 for a single bubble latch, implying that it is enough to perform transportation and manipulation of the tile, which we subsequently demonstrate. In the majority of cases, we observe that when a bubble link breaks, the bubble does not split into two but separates from one of the hubs cleanly. This suggests that the maximum force that a bubble can currently support is limited by the adhesion force between the bubble and SU-8 and does not correspond to the surface tension force of the bubble itself.

3.3. Rigid-to-Flexible Transition and Structural Reconfiguration. Bubbles hold another important advantage over droplet latching mechanisms in that they are highly compressible and can easily expand or contract according to external stimuli such as heat and pressure. This allows for an object to be able to transition between states of rigidity and flexibility without the need to disassemble. As Figure 5 shows, when first assembled, a system is aligned and is in its most compact form but is also stiff. When presented with a 90° bend in the channel geometry, it becomes stuck, prohibiting any further transport. By reducing the pressure inside the channel, the bubbles expand, causing the chain of tiles to loosen and allowing the structure to snake around the turn. After the tiles pass the corner, the pressure is increased, contracting the bubbles to their original size. The tiles realign, transforming back into their rigid, compact form before continuing down the channel (Movie S3).

By creating a bubble hinge at the appropriate corners of adjacent tiles, we are able to reconfigure a structure deterministically without disassembly. We demonstrate this by reconfiguring a structure among the five tetromino shapes found in the original Tetris video game. By starting with four tiles in a row (the I shape), we map out a sequence with which to achieve each subsequent shape (Figure 6a). In the experiments, each tile sits in front of a microfluidic port that the user can control either to inject or extract fluid, and the laser is used to create bubble hinges selectively. In Figure 6b–e and Movie S4, each of the

Figure 5. Rigid-to-flexible transition allowing the structure to pass through an obstruction (Movie S3). (a) Schematic diagram showing the rigid-to-flexible transition of an assembled object as it passes around a corner. (b) The tiles are stopped at the sharp 90° turn. When the pressure decreases, the bubble latches expand to add flexibility, allowing the chain to bend around the turn. When the pressure increases, the bubbles contract to make the system rigid again.

Figure 6. Tetromino reconfiguration demonstrations (Movie S4). (a) Schematic of the sequence that one can use to reconfigure from the I shape to each subsequent form. Experimental demonstrations show (b) I-to-L, (c) L-to-O, (d) L-to-T, and (e) T-to-Z reconfigurations. Arrows at the bottom of the images show the direction of flow through the ports. The scale bars are 100 μm.
reconfiguration steps illustrated in Figure 6a is demonstrated. In Movie S4, the demonstrations are compared to reconfigure experiments done without creating a bubble hinge, which results in the disassembly of the original structure.

Performing various functions in a system requires the assembled structure to balance flexibility, where components are linked by a single bubble, with structural integrity, where they are linked by multiple bubbles. As we showed, both the bending and reconfiguration demonstrations are easily achieved when only one bubble is used to link the components. Therefore, relatively weak fluid forces as identified by our force analysis are needed to transport, bend, or reconfigure structures as to avoid accidentally breaking a bubble link. At the same time, if the disassembly of a structure is desired, then stronger forces can be applied to separate the tiles without damaging them, unlike systems with mechanical latches where structural damage may be a problem. In the technique’s current state, the ability to create bubbles on command still allows for any bending, reconfiguration, or reassembly steps to be taken first, and then the system can be made more robust by adding more bubbles. In this sense, a structure can still be both flexible and structurally robust at different points in time.

4. CONCLUSIONS

In this article, we have characterized and demonstrated laser-activated bubble latching as a novel technique for assembling, transporting, and reconfiguring microstructures. This method brings together the advantages of both surface tension-driven self-assembly and microfluidically directed assembly and presents several new functionalities. The control over latching locations affords a large degree of freedom in the assembly of components into arbitrary and complex structures. Utilizing the compressibility of bubbles allows for the rigid/flexible transition of objects, which is particularly useful for structures that need to navigate through complex channel geometries. Bubble hinging at tile corners provides a quick and accurate way to reconfigure structures after assembly. Laser-activated bubble latching, which supports a simple design, provides greater assembly control to the user, demonstrates novel capabilities, and is a promising method for programmable microscale assembly applications.

ASSOCIATED CONTENT

Supporting Information. Details of the bubble growth data and characterization, the sticking issue between the tiles and the PDMS, and movies showing the experiments that have been described above. This material is available free of charge via the Internet at http://pubs.acs.org.

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