MEMS

Some Self-Assembly Required

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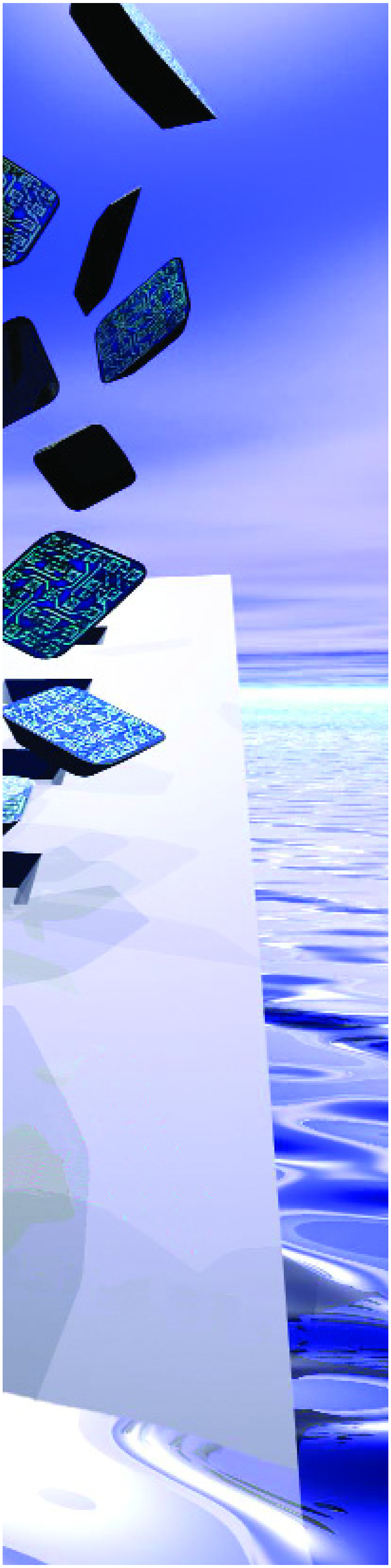
Fluidic self-assembly can provide the vital step in the fabrication of chip-sized optical MEMS for a wide variety of applications. Nature herself provides an inspirational model for fluidic self-assembly, as well as useful guidelines for processes that can be employed to build microsystems. In this review article, we describe some achievements in assembly that have already been demonstrated, including our own research on fluidic self-assembly of micromirrors for an adaptive-optics array. The results reported to date lead us to predict significant growth in the applications to microsystems of fluidic self-assembly techniques.



Let's take a lesson in microassembly from an expert in nature, the abalone. The abalone coats its shell with a layer of mother-of-pearl that not only reflects luminous rainbows of color, but is also twice as hard as any man-made ceramic. Designed to protect the mollusk from hungry sea otters, the material in fact can be broken only by use of industrial machinery; and instead of cracking like a ceramic, it deforms like a metal. This uncommon strength is derived from a unique microstructure: hexagonal disks of crystalline calcium carbonate are stacked brickwise with a polymer mortar. This way, any cracks that form must follow zigzag paths, and thus do not grow to fatal dimensions. To build such a composite, first the abalone actually creates the mortar matrix by secreting a polymer solution that self-assembles into a three-dimensional network of chambers. Then, by releasing a particular protein, each seawater-filled room is wallpapered with nucleation sites so that the limestone crystal bricks grow spontaneously. The manner in which this material is formed demonstrates one of nature's most powerful manufacturing techniques: templated self-assembly. In this paradigm, interactions between objects and defined features in their environment determine the final structure. To top it off, nature's elegant assemblies are achieved under mild conditions with minimal waste.[1]

What can we take away from the abalone's seventy million years of experience to help solve our own microassembly dilemmas? Given our current techniques, the assembly of various optical microcomponents onto a single substrate, although highly attractive, poses formidable challenges. But in nature, spontaneous processes to assemble ordered structures with up to millions of components are commonplace. Based on nature's success, there is compelling motivation to draw upon the principles of self-assembly.[2] One class of self-assembly, defined as "spontaneous organization of molecules or objects into stable aggregates under equilibrium conditions," is commonly seen in crystal formation and protein folding.

In this article we review recent efforts to develop fluidic self-assembly techniques for positioning microcomponents onto a substrate, including a technique we developed that uses capillary forces. But first, we discuss the rationale for using microassembly techniques for optical microelectromechanical systems (MEMS) and explain why self-assembly approaches are attractive for this purpose. Finally, we discuss results from an application of our technique to solve one problem the designers of optical MEMS face: mirror flatness.

Why microassembly?

In the past five years, applications of MEMS to optical systems have multiplied. Most evident are mirror arrays for fiber-optic switching and MEMS projection displays. However, before we can realize the full potential of micro-optical systems, we must be able to integrate, onto a single substrate, various optical components—lenses, diodes, mirrors and filters—made from diverse materials. The fabrication of different devices in a single process has encountered roadblocks caused by materials and process incompatibilities, in particular between III-V semiconductor materials and silicon. For this reason, making the devices in separate processes and using assembly techniques to integrate them appears at this time to be the most promising

Figure 1. Fluidic self-assembly technique developed by Alien Technology.

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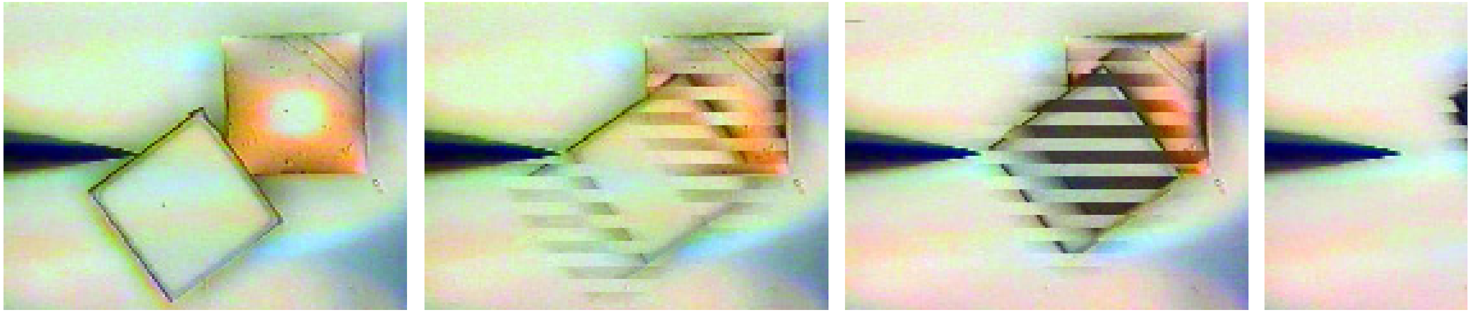

path to building complicated micro-optical systems. Adding to the obstacles, optical applications often impose stringent assembly requirements: submicrometer alignment precision and less than a milliradian of rotation. To achieve these specifications, flip-chip and other "pick-and-place" techniques require complex robotic systems that are constrained by speed and cost. For these reasons, researchers around the globe are pursuing parallel assembly methods in which large numbers of microparts (tens of thousands to millions) may be positioned simultaneously. These techniques can be divided into two categories, wafer-to-wafer transfer and self-assembly. In wafer-to-wafer transfer, the microcomponents are organized on a donor wafer before they are transferred to the target wafer. In self-assembly, the microcomponents are freed into solution and then randomly directed towards a substrate that contains binding sites at the desired locations.

Microassembly by self-assembly

Self-assembly is an intriguing approach to solving the problems of microassembly. Binding sites for templated self-assembly can be defined not just photolithographically, but also by stamping or printing. Therefore, microcomponents can be assembled onto very large substrates having a variety of materials and/or shapes. Second, expensive materials, such as the III-V semiconductors needed for lasers, can be used most efficiently because they are distributed only where required rather than batch-transferred in a wafer-bonding approach. In addition, sorting out defective parts before the self-assembly process can lead to significant improvements in yield and reductions in cost.

Of course, there are important challenges to developing production-level self-assembly methods. Most importantly, techniques are needed to provide electrical and mechanical connections to the substrate. Also, given the importance of surface forces at the micro level, a lubrication scheme may be needed so that parts can move freely over the substrate. Another important challenge is to specify the orientation of the assembled microcomponents, since they tumble in random orientations in the carrier fluid.

To many observers, the benefits of this new approach appear to outweigh its challenges. Consequently, research groups worldwide are developing self-assembly methods to position microcomponents onto various target substrates. The general approach is as follows. Matching binding sites on the microcomponents and those on the target substrate are defined, typically using photolithographic methods. The receptor binding sites on the substrate act as potential-energy wells for the shape-matched binding sites on the microcomponents. To initiate the self-assembly, the microstructures are freed from the substrates on which they were fabricated and transported towards a target substrate in a carrier fluid. Fluidic transport is the method of choice because surface interactions, which dominate at this size scale, are easier to control in a liquid environment. When the binding sites come into contact, there is a probability that the part will "fall" into the energy well and spontaneously align itself to minimize energy. If the part escapes before attaching, it is carried away by the fluid and can be transported to another site. As the assembly process continues, the microparts fill the vacancies on the target substrate.

To ensure high assembly yield and alignment accuracy, the part and substrate binding sites must be carefully designed. First, the desired assembly configuration should represent a minimum potential-energy state. Second, any energy barriers, or local minima in the potential-energy well, should be small compared to the potential-energy difference that drives the assembly. To help microcomponents attain minimum-energy positions, a lubrication method should be employed. Also, random kinetic energy in the form of fluidic agitation or ultrasonic vibration can be applied to reduce energy barriers or to disassemble any incorrectly assembled parts.

Recent efforts

A notable self-assembly technique developed by Smith and coworkers uses gravitational and hydrodynamic forces to place trapezoidally shaped microcomponents into similarly shaped holes in a target substrate (Fig. 1). The parts are fluidically transported across the substrate in water. Once assembled into the holes, they are held in place by gravity, by van der Waals forces, and upon drying, by capillary forces. The assembly is then laminated to affix the parts permanently. Because the planarity of the substrate is regained upon assembly, electrical connections can be patterned using standard photolithographic techniques. The integration of GaAs light-emitting diodes onto silicon substrates has been demonstrated by use of this procedure. A spin-out company, Alien Technology, Morgan Hill, California, has commercialized the technique into a mass-production manufacturing process to make inexpensive displays by assembling integrated circuits onto continuous rolls of plastic films. The assembly of tens of thousands of components per minute with 1-μm accuracy and 99.99% yield has been demonstrated, proving that self-assembly is a viable manufacturing approach to microassembly.[3]

Other research groups are using a variety of forces to achieve attraction and binding of microcomponents onto a substrate. Cohn, Böhringer and coworkers have used electrostatic traps as energy wells to assemble ~100-μm-long polysilicon parts onto a substrate in vacuum.[4] To

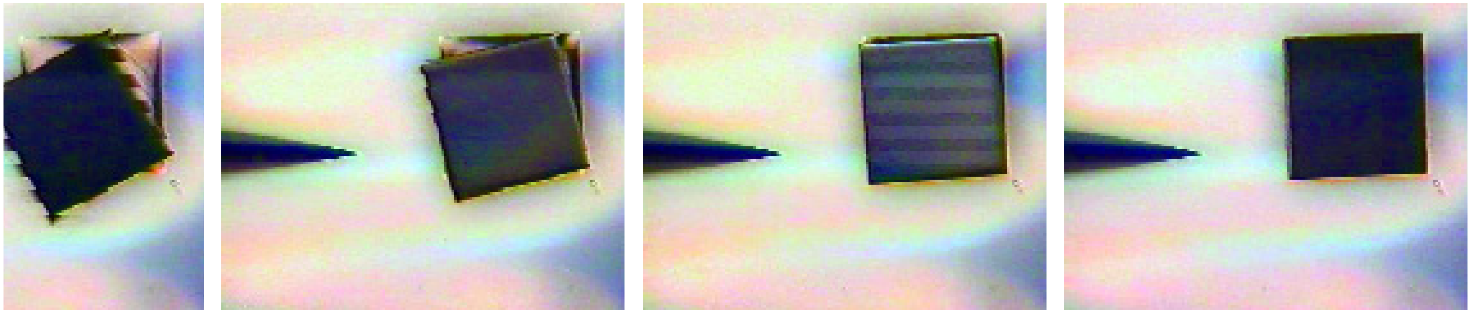

Figure 2. Video frames of a self-assembly event taking place within one second. The part is 400 μm on a side and the probe tip is used only to bring the part into contact with the binding site.

overcome energy barriers from friction and adhesion forces, the group vibrated the substrate using ultrasonic transducers.

In another self-assembly technique, Nakakubo and Shimoyama assembled 100-μm cubes together using polymer bridging and shape complementarity.[5] Magnetic forces were applied by Murakami and coworkers to attach 50-μm-diameter metal disks in water onto a substrate patterned with arrays of nickel binding sites.[6] Although binding was observed, alignment did not occur because there was no lubrication to reduce friction. In work done by Esener and coworkers, coulombic forces from negatively charged DNA were used to assemble ~10-μm-diameter GaAs test parts onto positively charged receptor pads on a silicon substrate.[7] Once the parts were positioned, bonding took place between complementary DNA strands attached to the part and substrate sites.

Micro-self-assembly using capillary forces

The success of a micro-self-assembly technique depends on the specific forces chosen for attachment and binding. Certain forces become dominant in the microdomain because of their fundamental scaling properties, while other forces that may be familiar to us at the macroscale lose significance. Capillary, or surface-tension forces, in particular, scale very favorably as the size of the system is reduced, as is evidenced by the ability of some insects to walk on water. At the microscale, in fact, capillary forces dominate over many other forces that scale with higher powers of size: gravitational, hydrodynamic, magnetic, electrostatic and surface-adhesion forces.

Using capillary forces, Whitesides and coworkers at Harvard University have developed techniques to self-assemble millimeter- to centimeter-sized plastic parts into aggregates and three-dimensional arrays. Their technique involves a method of coating selected faces of the assembling objects with thin liquid-adhesive films and agitating them in a second liquid medium (with which the lubricant is insoluble) so that the films on the binding faces can coalesce.[8] The lubricant film and the medium are chosen so that the interface between the two has a high interfacial free energy, making it energetically favorable for the lubricant-coated faces to join and self-align, thereby minimizing the exposed lubricant-medium interfacial area. Based on the advantageous scaling of capillary forces at the microlevel, we have extended the technique of the Whitesides group to self-assemble micromachined silicon parts onto silicon and quartz substrates in preconfigured patterns.[9]

In our process, self-alignment takes place between matching binding sites with a meniscus formed of liquid adhesive between them. Video frames from a self-assembly event are shown in Fig. 2. Because the capillary films that drive self-assembly also act as lubricating layers, submicrometer positioning precision (″ 0.2 μm) has been demonstrated. In addition, with capillary forces much stronger than fluidic-drag forces at the microscale, this technique provides high assembly yields: 100-part arrays have been assembled with 100% yield in less than 1 min. With these promising results in mind, we applied our method to address micromirror flatness, an important problem facing the optical MEMS community.

Mirror, mirror on the microactuator

Movable MEMS micromirrors have been applied for several purposes, including optical switching, displays, adaptive optics and optical-data storage. Generally, a high-quality micromirror needs to be smooth, flat and highly reflective. Also, a MEMS mirror may need to have a low mass for applications in which scanning speeds are in the kHz range. Various applications impose different requirements on the micromirror surface. For scanning mirrors and those for adaptive optics, the micromirrors need to be flat to within $\lambda/20$ rms (and preferably $\lambda/40$ rms) during dynamic deformation. For red light (λ = 632 nm), this necessitates a surface flatness within 32 nm rms (and preferably 16 nm rms) across a micromirror surface ~1 mm in diameter. These criteria are especially challenging because MEMS mirrors are often fabricated from thin films.

To attain such high-quality micromirrors for a MEMS application, we applied our micro-self-assembly technique to place single-crystal-silicon mirror segments onto surface-micromachined actuators.[10] Together, the actuators and mirrors form a segmented deformable mirror for use in an adaptive-optics system. In this application, the stiffness requirements for the actuators and the mirror segments are diametrically different. While the actuators need to be supple enough to move the mirror segments more than 5 μm in the vertical direction, the mirror segments must remain flat to within 30 nm rms. Assembling the mirrors onto prefabricated surface-micromachined actuators allows us to decouple the elements and thereby to concentrate separately on the fabrication processes of each one.

The basic steps in the assembly process are depicted in Fig. 3. First, the surfaces of the mirrors and the microactuator substrates are separated into hydrophobic and hydrophilic regions, where the hydrophobic shapes will serve as the self-assembly binding sites. Next, the mirrors are freed from their host wafer into solution.

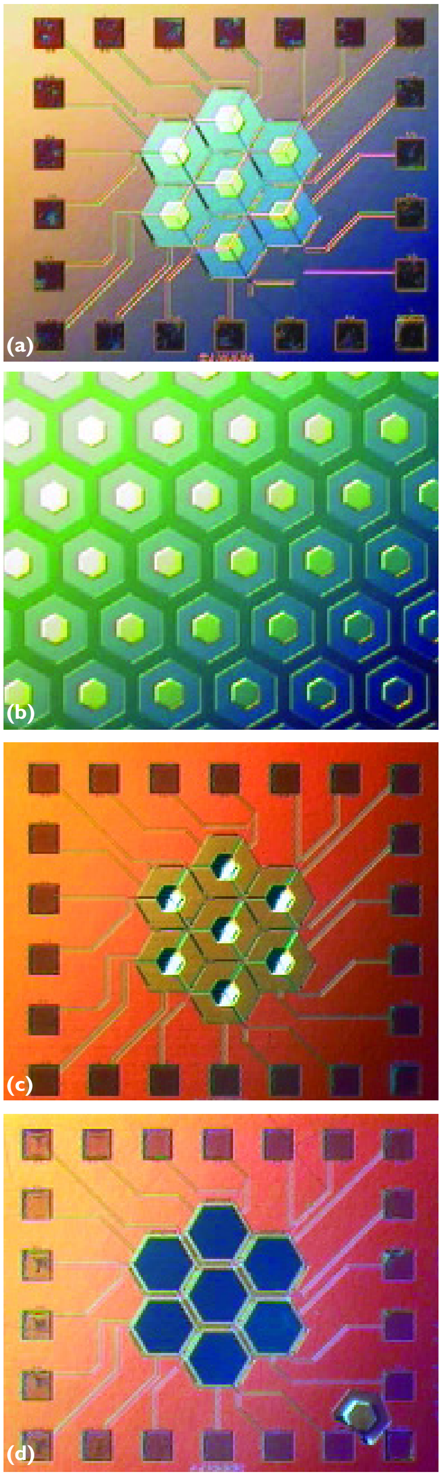

Figure 3. (a) Array of surface-micromachined actuators with hexagonal Au/Cr binding site for mirror attachment. (b) Array of Si (100) mirrors with Au/Cr binding sites, fabricated from SOI wafer with silicon thickness of 20 μm. (c) Actuator array with acrylate adhesive selectively coating the hydrophobic gold binding sites under water. (d) Actuator array with self-assembled mirrors under water. The unbound, upside-down mirror in the lower right was later removed with flowing water.

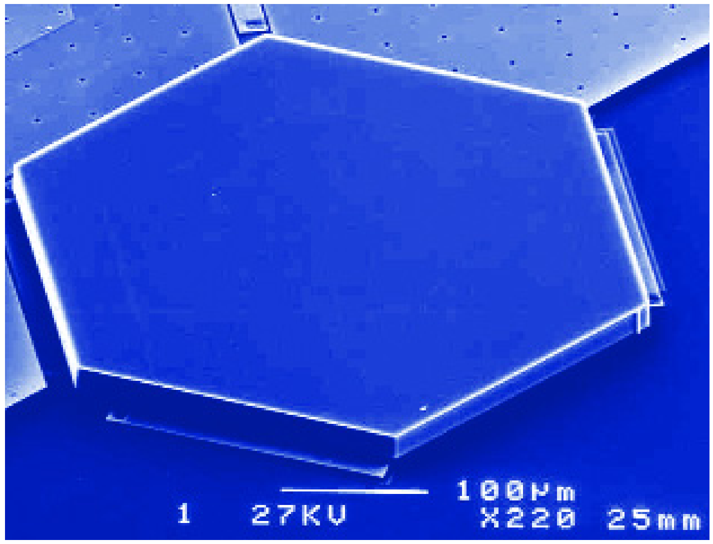

Figure 4. Single crystalline micromirror self-assembled onto surface-micromachined actuator for an adaptive optics application.

To coat the hydrophobic binding sites on the microactuator substrate with an adhesive/lubricant liquid, the patterned substrate is passed through a film of hydrophobic liquid adhesive on water, causing the adhesive to coat only the binding sites. To perform the self-assembly, the released mirrors are directed towards the submerged substrate surface using a pipette. When a hydrophobic pattern on a mirror comes into contact with an adhesive-coated binding site on a microactuator platform, shape matching occurs spontaneously because of interfacial free-energy minimization. The assembled mirrors are held in place in water by the capillary forces of the adhesive; unbound parts can be removed using flowing water. Once the assembly is complete, permanent bonding is achieved by heat-curing the adhesive. Finally, the assembly is removed from water, dried and the microactuators are released using a supercritical carbon dioxide process.

Figure 4 shows a 20-μm-thick mirror segment assembled onto a microactuator platform. The flatness of the assembled crystalline mirror was measured to be better than 3 nm rms. In contrast, without the assembled mirror, the microactuator platform exhibits over 1 μm of deformation. In this case, microassembly makes it possible to fulfill the adaptive-optics requirements for a high-quality optical surface without compromising microactuator design.

Conclusions

Efficient microassembly techniques are very useful, and in many cases indispensable, to the field of optical MEMS and micro-optics. Various MEMS and micro-optical components can be fabricated in separate, optimized processes, and then integrated onto a single platform. Candidates for microassembly include micromechanical components such as mirrors, lenses, gratings and beam splitters, as well as optical devices such as photodetectors, light-emitting diodes and lasers. To scale up the self-assembly techniques described in this article, fluidic part delivery and recycling systems must be designed to assemble large arrays with high yield. In addition, we can envision refining such techniques to assemble different sets of microcomponents sequentially onto a single substrate by using different classes of binding sites. As a microassembly approach, self-assembly can help us to realize complex and powerful micro-optical systems.

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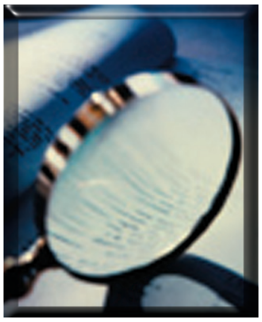

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Biomedical Applications of Fluorescence Lifetime Imaging 26

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