

Self-Assembly for Micron-Scale Robotics

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Abstract—Self-assembly of microfabricated components provides a powerful method for integration and mass manufacturing of heterogeneous integrated systems such as micron-scale robots. We have developed a number of processes for making micron-scale functional components, such as transistors, that can participate in a self-assembly process and have investigated their organization into two and three dimensional structures driven by capillary forces resultant from molten alloys and polymers.

Index Terms— self-assembly, micron-scale robotics, nanofabrication, microfabrication, heterogeneous system integration

I. INTRODUCTION

THE aggressive progress of microelectronics industry in the past few decades has made access to powerful integrated circuits consisting of a large number of electronic devices possible. The extension of the fabrication techniques used to make integrated circuits to the non-electronic domain, as manifested in microelectromechanical systems (MEMS), has provided a new ability to not only make miniaturized circuits but to construct micron-scale devices such as micromirrors, micropumps, and various microactuators. Although the solid-state microfabrication technology has been very successful in making these devices, it has been markedly less successful in making miniaturized systems comprised of multiple different types of components. Construction of a micron-scale heterogeneous system—such as a robot that incorporates actuation, sensing, telecommunication, and basic decision making—has proven to be extremely challenging. Two major obstacles in mass-producing such multifunctional micron-scale systems are: A) the incompatibility of many of the microfabrication processes used to make the components of a single system. For example most circuits are built on silicon substrates, optoelectronic devices are constructed on crystalline compound semiconductor substrates, and many sensors use polymers and other organic molecules in their structures making the fabrication processes used to make these devices incompatible with each other. B) Most solid-state microfabrication processes rely on photolithography for pattern generation and are inherently two-dimensional (2D).

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Although techniques such as deep reactive ion etching and soft-lithography have enhanced the geometric capabilities of solid-state microfabrication, a fabrication technique that can mass-produce an arbitrarily-shaped 3D microstructure made of multiple materials has not been developed to this date.

Self-assembly is a manufacturing approach that can potentially both circumvent process incompatibility issues for system integration and afford 3D micron-scale structures [1]. We define self-assembly as the spontaneous organization of a collection of components into a higher ordered structure. In the context of micron-scale system integration and robotics, self-assembly can be regarded as a process that guides a collection of independently microfabricated components into forming an interconnected functional system. Self-assembly is an inherently parallel manufacturing method that does not require top-down supervision and in principle, can be used for very high volume manufacturing of heterogeneous microsystems.

In order to construct a micron-scale system or robot via self-assembly, a number of issues must be addressed: A) techniques must be developed to generate a large number of functional micron-scale components that can participate in a self-assembly process, B) binding forces must be identified to enable structure formation and programming methods must be identified to guide the self-assembled system towards a final, pre-defined outcome, and C) self-assembly procedures must be developed to allow for high yield production of micron-scale systems.

Our group has embarked on an extensive program to study all aspect of a mass-manufacturing method to produce micro-scale heterogeneous systems via self-assembly. In the nano-scale, we have used custom-synthesized organic molecules and covalent bonds, DNA hybridization, and genetically engineered polypeptides [2] to place nano-scale objects onto templates and self-assemble structures from the bottom-up. In the micro-scale, we have primarily relied on microfabrication to make the parts and have taken advantage of capillary forces to self-assemble larger structures. In the following two sections we discuss two examples of micron-scale self-assembly for creation of 2D and 3D structures from a collection of independently microfabricated components.

II. 2D SELF-ASSEMBLY

We have developed methods to generate free-standing micron-scale components such as field effect transistors, photosensors, and light emitting diodes that can participate in a capillary force driven self-assembly process. Development of such methods to generate parts for self-assembly is a critical step in mass manufacturing of micron-scale heterogeneous systems. Figure 1 shows the microfabrication

processes used to make a collection of microcomponents. The details of the microfabrication process and the usage of these components in self-assembly are provided elsewhere [3].

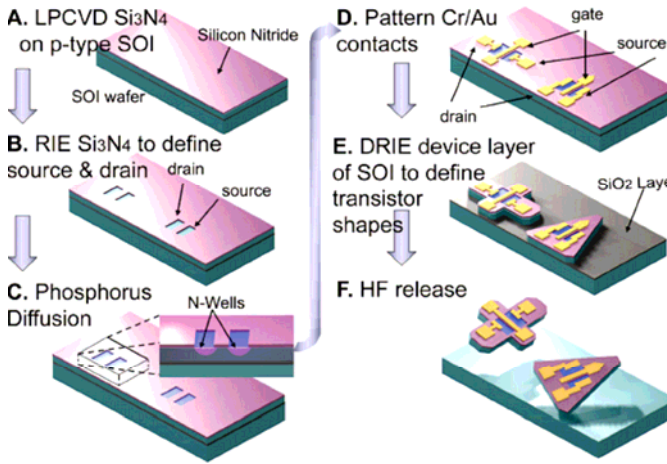


Fig. 1. Fabrication process for making free-standing single crystal field effect transistors to be used in the self-assembly process.

Figure 2 shows a collection of microfabricated components forming a powder-like substance and the measured performance of a typical transistor verifying the appropriate functionality.

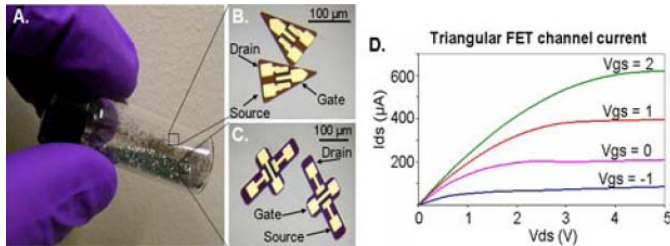


Fig. 2. Fabricated and released transistors. As shown in (B) and (C) the shape of the components can be easily controlled in the microfabrication process. (D) shows the measured device performance.

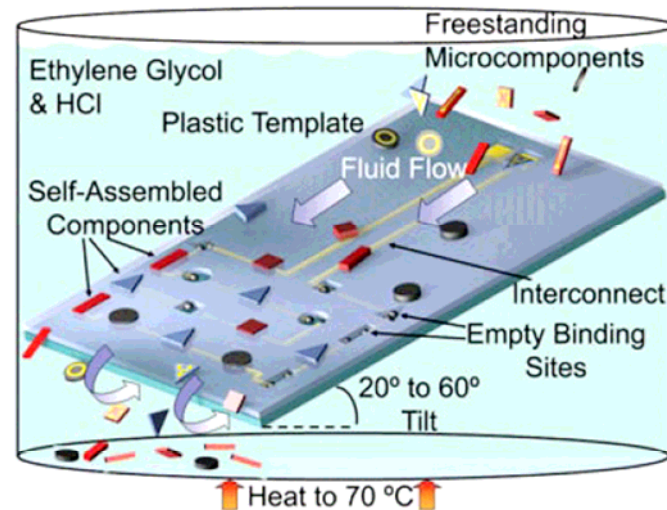


Fig. 3. Self-assembly procedure

We self-assembled these and similar single crystal micromachined parts onto a plastic templates in a fluidic medium as shown in Figure 3. We submerged a flexible

plastic template containing binding sites with specific geometry and interconnects in a low-pH heated fluid and introduced the powder-like collection of the parts in the environment. When the shape of the free-standing part and the binding site on the template matched (Figure 4), the part dropped in the correct location. A molten alloy placed at the bottom of the binding site made a connection between the metal interconnects on the template and the metal pads on the component. After the completion of the self-assembly process, the fluid was cooled down to solidify the alloy and make the mechanical and electrical connections permanent.

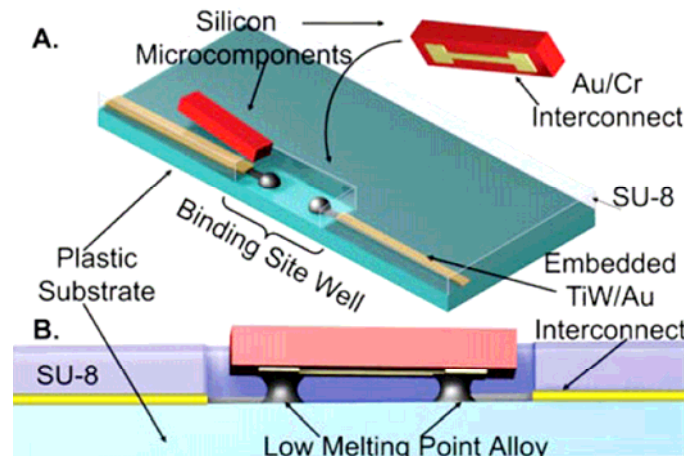


Fig. 4. Details of the self-assembly process. The capillary forces resultant from the molten alloy hold the part and template together.

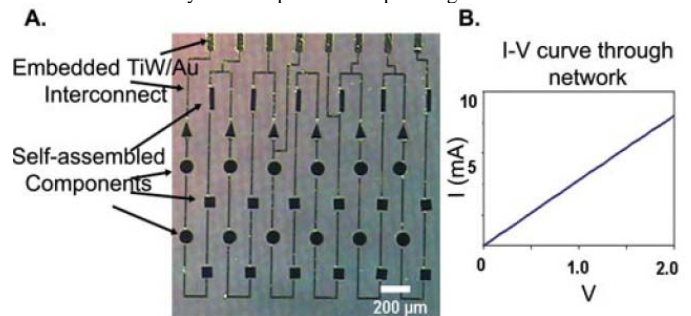


Fig. 5. Heterogeneous self-assembly results. (A) a 2D template completed with 4 types of components. (B) shows the measured interconnect resistance.

A. Plastic template with 10,000 binding sites and over 97% self-assembly B. Close-up of template showing ~2000 self-assembled components

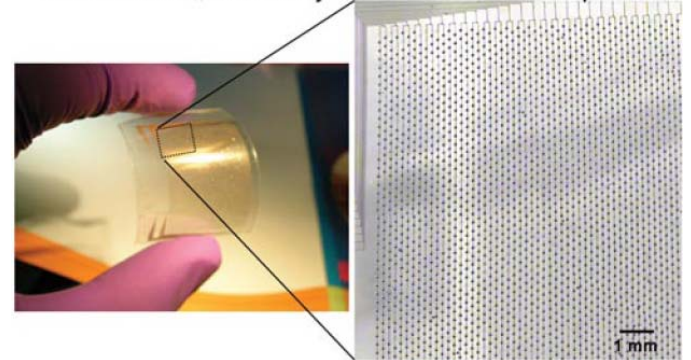


Fig. 6. High yield self-assembly results. The plastic template contains 10000 binding site. It has been completed by 100 µm single crystal silicon components with more than 97 % yield

Figures 5 and 6 show examples of self-assembled components onto a 2D template. We have demonstrated that a) shape recognition can be used to program the self-assembly

process and to assemble multiple types of components onto the right locations on a template, b) functional electronic circuits can be constructed on plastic with this method, and c) high self-assembly yield, approaching 97 % are readily achievable. This simple demonstration has generated operational circuits on plastic with measured mobility of $592 \text{ cm}^2/\text{V}\cdot\text{s}$, the highest values reported to this date.

III. 3D SELF-ASSEMBLY

Although 2D self-assembly as demonstrated above can be utilized in a wide range of applications from macroelectronic circuits to large area, flexible displays, more work is needed to build a 3D micro-scale functional system without a template guiding the growth. We have investigated both molten alloy and polymer capillary force driven self-assembly of micron-scale components suspended in a fluid medium as a means for constructing 3D interconnected structures from a collection of independently batch microfabricated parts.

Figure 7 shows the process for making and functionalizing the parts and also the procedure used to self-assemble them into 3D structures. The experimental details are provided elsewhere [4]. The design philosophy relies on our ability to cover specific areas on a micro-scale part with different types of molecules and engineering the respective surface energy. When a part with appropriate surface energies is submerged in a fluid medium, it is possible to take advantage of controlled precipitation and engineered solubility to deposit a material of interest on its surface. In our design, we have used thiols and silanes to render various regions on the body of the micro-scale components hydrophilic or hydrophobic. Subsequently, a hydrophobic polymer was selectively deposited on the hydrophobic sites on the structure of the parts with controlled insolubility variation. The polymer areas on the parts are drivers of the self-assembly process. As shown in Figure 7, when a collection of parts with a liquid polymer positioned on specific areas are allowed to move and collide in a fluid medium, the joining of the polymer regions can bring them together and form a bond between the two parts. The process can be allowed to proceed for an extended period of time after which the temperature of the self-assembly vessel is increased temporarily to solidify the polymer and make the bonds between the parts permanent. As shown in Figure 7, we have aimed at making an extended 3D structure with triangular components functionalized with self-assembled monolayers and polymer volumes.

Figure 8 shows some of our experimental results following the above procedure. We have been able to successfully cover the parts with molecules and polymers and have begun the experiments verifying their appropriate self-assembly into 3D shapes. Depending on the boundary conditions and agitation, the parts can form extended 2D or 3D shapes. Figure 8d, shows a 3D structure grown from the bottom up by self-assembly.

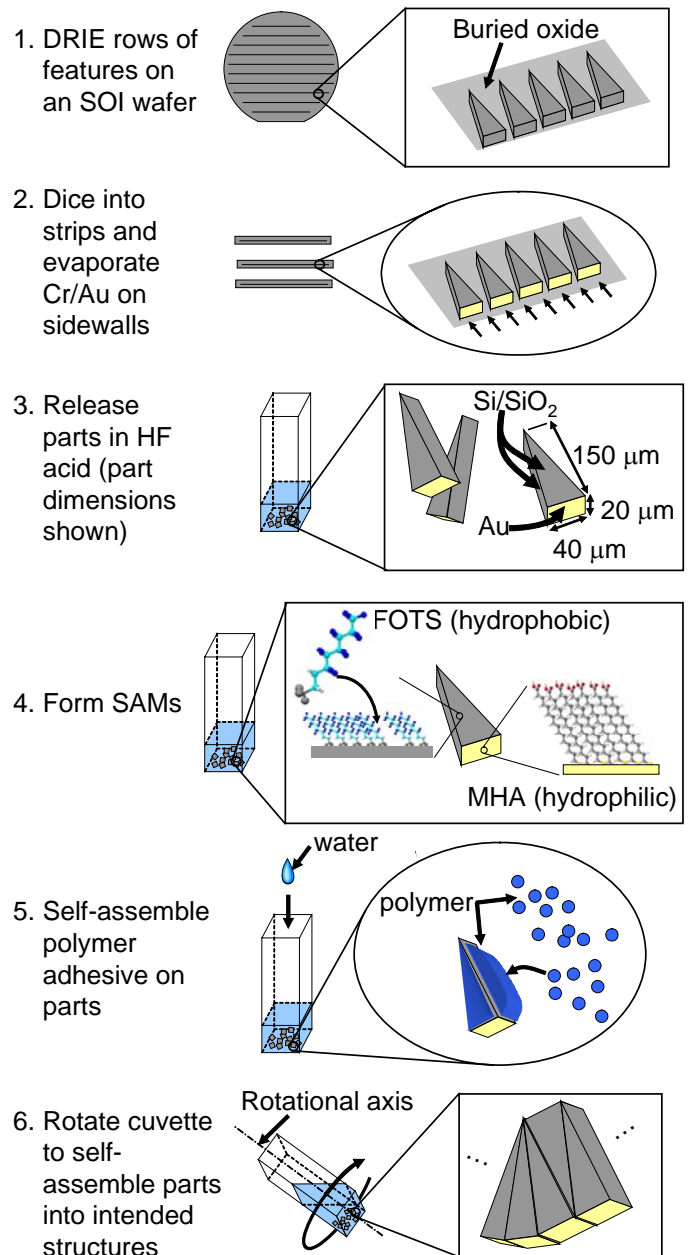


Fig. 7. Microfabrication and functionalization of the parts and their self-assembly into a 3D structure. The fabrication process begins with a photolithography step on an SOI wafer followed by deep reactive ion etching down to the buried silicon dioxide and removal of the resist. Rows of components are then diced and angled evaporation is used to coat one side of them with Cr/Au. After metallization, the components are released by wet etching the buried sacrificial silicon with hydrofluoric acid. The release step yields a collection of free-standing parts. The gold-coated regions of the components are rendered hydrophilic by forming a COOH-terminated SAM. The exposed silicon areas of the components are rendered hydrophobic by forming a SAM from fluorinated silane molecules. To self-assemble the components, they are immersed in an ethanolic solution of a heat-curable hydrophobic polymer. Gradual addition of water to the solution makes the polymer insoluble in the water/ethanol solution forcing it to leave the liquid. As the polymer exits the solution, the hydrophobic areas on the component offer a surface with favorable energy for its assembly. Using this method, micron-scale suspended parts can be coated with polymer only on previously specific locations. Once the polymer deposition is complete, the parts are allowed to move around and collide. The addition of two polymer regions brings together the associated components. Once the self-assembly is complete, the structure can be fixed by heating the linker polymer.

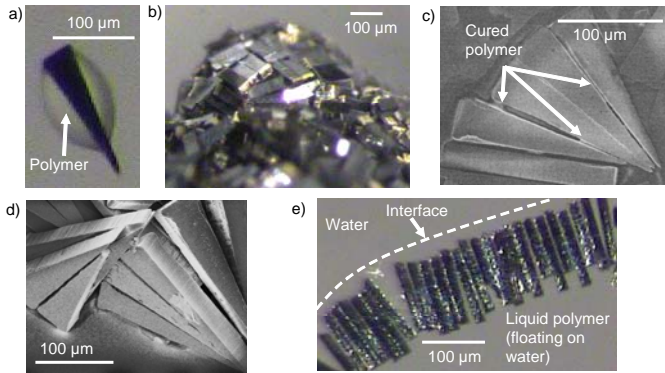


Fig. 8. Results from applying the polymer deposition method to the self-assembly of triangular, microfabricated silicon parts. a) One unassembled part with a significant amount of polymer on its hydrophobic faces. b) A large collection of microparts which were allowed to self-assemble after the polymer deposition method, but all parts quickly and randomly aggregated together due to a large amount of polymer that was deposited. c) Scanning electron microscope (SEM) image showing the self-assembly of a small number of parts into the desired configuration, with cured polymer visible between the parts. d) SEM image showing the self-assembly of a small number of parts from a different experiment. e) A collection of stacked triangular parts floating near the edge of a polymer droplet on a water surface. The parts and polymer were originally submerged, but the few shown had floated to the surface during agitation, making an ordered 2D structure grown without a template to guide the process [4].

IV. CONCLUSION

Self-assembly provides an extremely powerful method for manufacturing 2D and 3D heterogeneous systems from microfabricated components. The examples detailed above show that the components for self-assembly processes can be readily generated and allowed to self-assemble onto 2D templates or into 3D shapes. Much more extensive efforts are needed to define and perfect the methodology to ‘grow’ an arbitrary shape from a collection of microfabricated parts. So far, we have been primarily limited to repetitive patterns of simple parts. During the course of our investigation we have determined that two key issues must be addressed in the development of any mass-manufacturing method relying on self-assembly. The first issue is the reliability and scalability of the electrical interconnects. We have observed that large connections made using the capillary interactions from a molten alloy between two metallic surface work rather well; however, as the size of the connections is scaled to 10 μm and below, a number of new challenges arise including the oxidation and fast erosion of the alloy in the acidic self-assembly environment. Another area in need of systematic study is the method of agitation in a micron-scale self-assembly scheme. It is instructive to look at an analogous situation at the molecular scale. Many molecular systems rely on self-assembly for the formation of the final desired structure. In these systems, similar to the micron-scale self-assembly, a collection of parts moves around and makes temporary bonds. The system is driven towards its minimum

energy state via thermal fluctuations. These fluctuations allow for incorrectly formed bonds to break and guide the system to proceed in the right direction. Unfortunately, it is not clear what the analog of temperature may be in the micron-scale. Forces imparted on the components used in our self-assembly demonstration come from fluid motion, gravity, and component/component/container collisions. These ‘agitation’ mechanisms lack the randomness of thermal fluctuation at the molecular scale. The lack of the proper agitation method make the design and implementation of a self-assembly method much more difficult.

Despite challenges and difficulties, self-assembly for micron-scale system integration has made long strides towards the final aim of building a micron-scale robot from the bottom-up. Further investigation of molten-alloy capillary bond formation and modes of agitation for larger-scale systems can certainly accelerate the progress in the field.

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Babak A. Parviz (S’93-M’01-SM’06) received his BS in Electrical Engineering from Sharif University of Technology in 1995. He received his graduate degrees from the University of Michigan: MS in Electrical Engineering (1997), MS in Physics (2001), and PhD in Electrical Engineering (2001). From 2000 to 2001 he was a device designer and project manager at Nanovation Technologies Inc. From 2001 to 2003 he was a postdoctoral research fellow in the Department of Chemistry and Chemical Biology at Harvard University. Since October 2003, he has been with the Electrical Engineering Department at the University of Washington as an assistant professor. Babak Parviz has received a number of recognitions including the Bronze Medal from the 22nd International Physics Olympiad, 1st place in Kharazmi Award, the Distinguished Achievement Award from the EECS Department at the University of Michigan, and has been selected twice (2004 and 2005) to participate in the National Academies Keck Future Initiative. His areas of interest include: research at the interface between biology and electrical engineering (single cell biology, ultra-fast genome sequencing) engineered self-assembly, nanofabrication, and MEMS.