FABRICATION STRATEGY FOR MICRO SOFT ROBOTICS WITH SEMICONDUCTOR DEVICES INTEGRATION

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ABSTRACT

We report a general method to fabricate miniaturized soft robots. For the first time, a freestanding microscale robotic finger/tentacle has been realized by heterogeneous integration of soft material polydimethylsiloxane (PDMS), liquid metal (LM), and silicon chips. Unlike the existing methods to make soft electronics or soft robotics, our technique of heterogeneous integration enables large-area parallel manufacturing of micro soft robotics armed with distributed crystalline silicon, deformable microfluidic channels, and flexible electrical interconnections, bridging the gap between the state-of-the-art soft electronics on a continuous film and soft robotics spanned in centimeters.

INTRODUCTION

Inspired by nature, soft robots are expected to bring another dimension to the existing rigid machinery and to fundamentally change the electromechanical systems [1]. Soft components in micrometer size and integrated with high quality electronics are critical in making a soft robotic system. However, they have been found difficult to be fabricated albeit many fabrication strategies have been proposed.

First, it becomes extremely difficult to fabricate, transfer, and handle microscale soft components. This is because, comparing to common MEMS thin films with micrometer thickness, micro soft parts require all three dimensions to be at microscale. Existing soft material processing techniques such as soft lithography cannot produce high resolution isolated soft structures without residual films [2], [3]. Laser cutting approaches are serial process, cannot generate vertical sidewalls and smooth interfaces [4], [5]. Photolithography and traditional thin film micromachining of polymers, on the other hand, provide easy realization of micro parts, but those polymers are usually nonstretchable (e.g., SU-8, polyimide, PET, parylene, etc.).

The second challenge lies in the integration of electronics to soft materials. Existing solutions includes the utilization of conductive polymers [6], kinetic stamp-transfer of high performance semiconductor electronics [7], [8], and employing liquid metals in the form of microfluidic channels [9]. However, all of them have so far been only applied to a continuous thin film [6], [7], [9].

Here, we present an approach to enable massively parallel fabrication of high-resolution, isolated and discrete soft structures integrated with high performance crystalline electronic components interconnected by deformable and stretchable liquid metal filled in microfluidic channels.

DESIGNS

Isolated soft micro components

To realize freestanding micro parts made with soft material, we utilize a special mold to create isolated soft micro components. The molding approach is considered for its high throughput (e.g., parallel, large-area, etc.) nature and ease of scaling up for future applications. As shown in Fig. 1(a), the curing of a soft polymer (e.g., PDMS) in a regular mold results in residue films [10]. To eliminate such residue thin film, a narrow rim is introduced in the mold design with shallower drainage wells to provide a clean cut and transfer of soft parts, as shown in Fig. 1(b). By repeating this process, soft movable parts can be built from a multilayer stack via bonding.

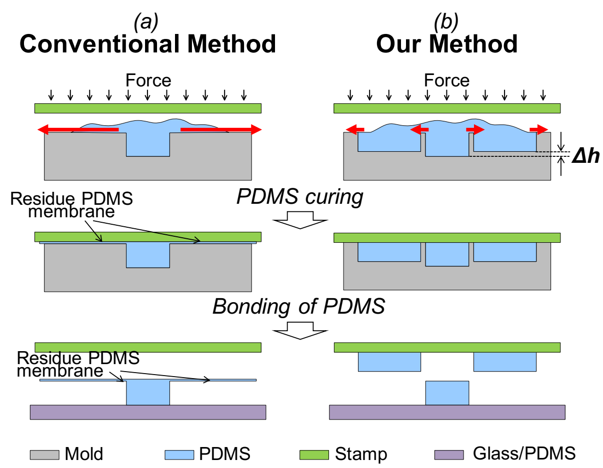


Figure 1: Comparison of methods to produce and transfer thin PDMS films. (a) Conventional method creates PDMS film by applying pressure against a mold with single well depth which leaves residue PDMS films (b) Our method utilizes a mold with narrow rims and different well depths (i.e., Δh) to transfer only the PDMS structure to the destination free of any residue PDMS film.

Integrated soft electronics with extended stretchability

Crystalline semiconductor is ideal for high performance computation but not stretchable. Therefore, instead of using purely semiconductor, we utilize liquid metal as links to connect distributed semiconductor devices (i.e., hubs). In combination of structured soft materials, the mechanical strain can be distributed mostly to the liquid metal links, leaving the semiconductor "hubs" under no strain and hence greatly extending the stretchability. Such stretchability ensures soft robots remained robustly electrically connected while being deformed or actuated.

FABRICATION

We designed a process to integrate liquid metal (LM), microfluidic actuation channels, and semiconductor devices. As an example, we demonstrate in Figure 2 a process to fabricate a PDMS finger/tentacle with a silicon (Si) chip at the tip connected with liquid metal and a microfluidic channel for structural deformation. After thermal oxidation, the Si chip and bonding areas were first patterned by reactive ion etching (RIE) SiO_2 and Si. Then thin PDMS layers were subsequently created and transfer-bonded to the silicon chip by O_2 plasma. Subsequently, the device was released by timed-etching the backside Si using deep reaction ion etching (DRIE) and isotropic etching. After device releasing, liquid metal was filled into the microfluidic channels and vias that connected with the Si chips. Note that pressurizing this microfluidic channel will lead to a deformation of the PDMS tentacle at the tip.

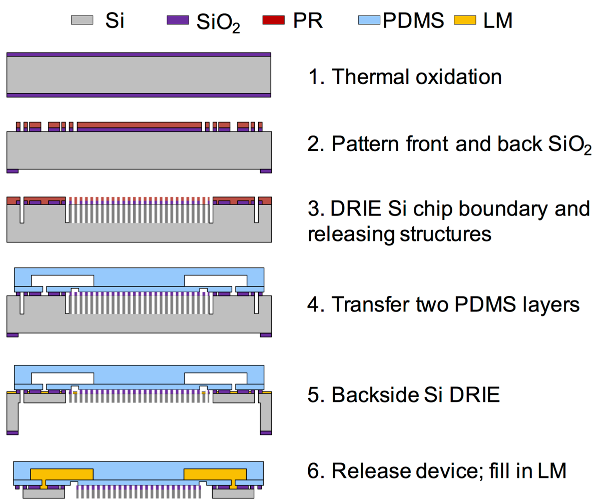


Figure 2: Sample process to fabricate a freestanding micro robotic tentacle with integration of PDMS, liquid metal, and silicon chips.

Step 4 in Figure 2 is the key step of our heterogeneous integration technique since it unifies our solutions to the abovementioned two key challenges in fabricating soft robotics. The process to achieve this multilayer isolated thin PDMS transfer is depicted in Figure 3. The Si mold with different well depths was fabricated by an embedded SiO_2 mask method, as described in our previous publication [11]. Learnt from literatures [10], [12], [13], the thin PDMS components were created and transferred as follows: Micro PDMS components were cured inside the Si mold against a fluorosilane treated glass under pressure (~4.5-8 MPa). PDMS was cured under room temperature and remained inside the Si mold after the glass was removed. We note that, to ensure distinct adhesion difference between the Si mold and the glass, we did ~4 times more fluorosilane on glass than on the Si mold. A hybrid stamp composing of a cured PDMS layer (~0.7-1 mm thick) and a photoresist-coated glass was used to pick up the top (i.e., ②) layer and align-bonded to the bottom (i.e., ①) layer. A transfer stamp ensures that the cured thin PDMS films maintained rigid and straight during transfer bonding. The two layer stacks of PDMS were then align-bonded to the Si device (Step 4 in Figure 2) using a commercialized aligner (Quintel 2001 Mask Aligner) and the photoresist-coated glass was removed by immersing the device in acetone. Note that the stacking of PDMS layers can go on if more layers are needed and the transfer to Si device can be used as an intermediate step or a final step, depending on specific design shape of micro soft components.

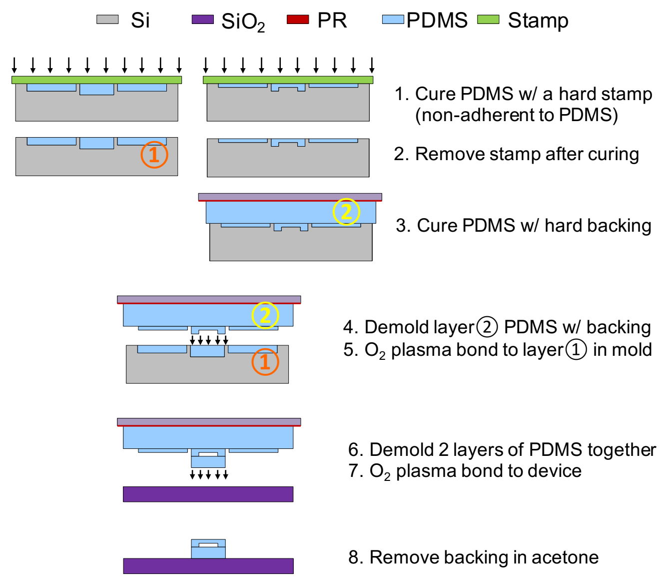
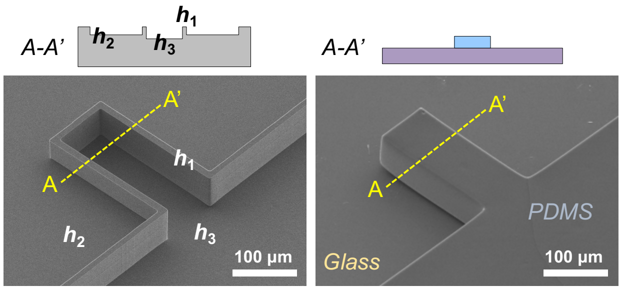


Figure 3: Process to create and transfer micro PDMS components. A two-layer PDMS stack is shown as an example: the top PDMS layer contains a microfluidic channel which seals when bonding to the bottom layer. Other than using upper layer to bond and pick up lower layers, separate transferring of each layer provides an alternative way of thin PDMS transfer.

RESULTS AND DISCUSSION

Isolated soft micro components

Figure 4 displays the fabrication results of a simplest micro PDMS component. Figure 4(a) shows an SEM micrograph of the fabricated Si mold with different well depths while Figure 4(b) demonstrates the transferred isolated PDMS microstructure on a glass substrate. The fact that neither unwanted residue PDMS was seen on the transferred PDMS nor PDMS from drainage wells were transferred confirms the effectiveness of our proposed method. Much more complicated micro components with different designs of embedded microfluidic channels were successfully fabricated following the same principle.



(a) (b)

Figure 4: SEM micrograph of the fabricated mold and transferred PDMS microstructure with cross-sectional schematics of A-A'. (a) Fabricated Si mold with different well-depth. h_1 =0, h_2 = -24 µm, and and h_3 = -64 µm. (b) Transferred PDMS microstructure bonded on a glass substrate with clean edge profile without any residue PDMS films hanging. Selective transfer has been confirmed since only the negative replicate of mold with depth h_3 has been transferred.

PDMS tentacle integrated with Si chip and LM

Figure 5(a) shows the fabricated freestanding micro robotic finger/tentacle integrated with Si chips at the tips without introduction of the liquid metal. The PDMS exhibits transparent while the Si chip looks opaque. Figure 5(b) shows the device with the liquid metal (Galinstan) filled to connect the Si devices. Liquid metal Galinstan shows a silvery mirror finish and electrically connects to the Si chip underneath. The bottom view of the device under SEM is shown in Figure 5(c). Note that the curved released shape of the device resulted from the film stress of the unwanted remaining silicon film on the backside.

In addition to effective transfer of isolated PDMS micro components, our method also makes PDMS displacement less insensitive to its location and surrounding patterns and thus serving for a large-area transfer. Since we utilized a commercialized photolithography machine for alignment bonding of different PDMS layers, errors in assembly using our approach would be similar to the traditional photolithography (~1 µm). To illustrate the large area transfer and accuracy of our heterogeneously integration method, Figure 6(a) demonstrates uniform 12 devices transferred placed on a 3×3.5 cm^2 area and Figure 6(b) showcases the accurate alignment between different PDMS layers and Si chips and releasing structures. The maximum alignment error in the entire transferred area was found to be < 2 µm.

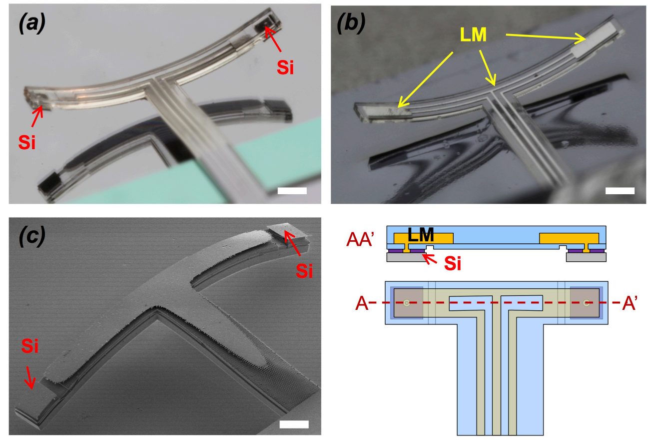
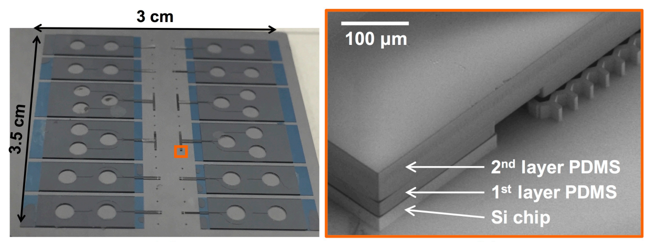


Figure 5: Fabricated PDMS tentacle. (a)Released device without LM showing transparent microfluidic channels and non-transparent integrated Si chips. (b) Device with LM filled and connected two Si chips at two tips. (c) bottom SEM image of the release device showing the Si chips and the releasing pattern. All scale bars represent 250 µm.



(a) (b)

Figure 6: Isolated PDMS micro components accurately align-bonded to the Si chip and releasing structures. (a) Alignment achieved in a large area of 3×3.5 cm^2 for a total of 12 devices. (b) SEM micrograph of the bonded PDMS layers to the Si chip and releasing structures. The cut of PDMS layers is clean and sharp, nearly the same as Si DRIE sidewalls underneath. The two well-aligned edges of the two transferred PDMS layers depict the high accuracy of bonding.

PDMS tentacle pneumatic actuation

Since we have also integrated microfluidic channels on to the PDMS tentacle, we demonstrate the pneumatic actuation capability of different expansion PDMS microfluidic channels in Figure 7. We did not fill in the liquid metal Galinstan in this experiment to better show the deformation of the channel. Expansion of the channel is preferred at the "joint" location where we designed a trench of PDMS (i.e., thinner PDMS). We foresee more complicated actuation can be achieved by concatenating a series of well-designed microfluidic channels and mechanical joints. This further confirms that our fabrication fully supports designs of micro soft robots in future designs.

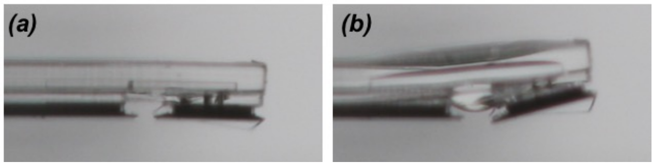


Figure 7: Robotic actuation capability demonstrated by pneumatic deformation of the PDMS tentacle tip. (a) Without pressure; (b) With pressure. Note that no LM is filled in this experiment to show to deformation more clearly.

CONCLUSIONS

We have presented a universal technique to fabricate soft micro components and integrate them with semiconductor devices and liquid metal (LM). We have demonstrated complete fabrication processes and an exemplary freestanding microscale robotic finger/tentacle. Large-area parallel manufacturing capability has also been shown. Since our technique overcomes the current limitation of making microscale soft parts and stretchable electronic circuits, we expect it will be particularly powerful in creation and exploration of miniaturized soft robots.

ACKNOWLEDGEMENTS

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